

Weed management in rice

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PLANT
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AND PROTECTION
PAPER

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Food
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Agriculture
Organisation
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United
Nations



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Edited by
B.A. Auld
and
K.-U. Kim

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PREFACE

Weeds are a major problem in rice crops, no matter where they are grown and no matter what production system is used. This book surveys the current status of weed management under various systems around the world. Although this has inevitably led to some repetition, each chapter stands alone and can be read independently of the other chapters.

Throughout the book, the emphasis is on an integrated approach to weed management. The dangers of relying on a single chemical method for instance are highlighted in chapter thirteen.

The book is aimed at research workers, extension officers and development agents with responsibility for assisting farmers with weed problems in rice.

On behalf of FAO, the editors sincerely thank all the authors for their efforts towards this volume and Mrs. Heather Smith and Ms. Maree Graham who assisted in the preparation of the final camera-ready copy.

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Notes on the use of this volume

Herbicide common names. Reference to herbicides is by their common names as approved by ISO and/or Weed Science Society of America, and as listed in the journals *Weed Abstracts* and *Weed Science* respectively. The occasional use of trade names is for clarity and infers no specific endorsement.

Herbicide uses and dose ranges. The indications of herbicides and dose ranges for use against particular weeds or in particular crops, in tables or in the text, are for guidance only and do not constitute recommendations. It is essential to check all such indications against local recommendations and regulations before any use by farmers. Doses, unless otherwise indicated, are in terms of kg active ingredient per hectare.

Disclaimer. The views and interpretations in this publication are those of the authors and should not be attributed to FAO or any other organization

CHAPTER 1

WEED CONTROL IN RICE

WEED CONTROL IN RICE

R. Labrada

INTRODUCTION

Rice is the leading cereal crop in the world. One third of the world's population depends on rice for nearly two thirds of its food. In densely populated areas of Asia rice is the main food. Rice is grown in more than 146.5 million hectares and is mainly produced by two principal methods: direct-seeding and transplanting.

World rice production reached 527.8 million tonnes in 1992 of which 95% was produced in the developing world. Far East Asia is the leading rice producing region with 91% of world production (FAO 1993a). Global output of rice is projected to increase at an annual rate of just under 2% to 409 million tons (milled terms) by the year 2000. This growth is driven mainly by continued improvements in yields through advances in plant technology as well as improvements in the application of inputs and irrigation (Yap 1994).

Although in 1992 rice production increased 1.5% in comparison to 1991 there is a shortage of rice in many developing countries, particularly Africa and Latin America, which are still compelled to import up to 10.2 million tonnes, worth of US\$ 2.04 billion (FAO 1993b). In Africa, rice is expected to continue to increase in importance, partially displacing staple foods, such as roots and tubers, as well as plantains, especially in the urban areas. This trend is likely to be the same in Latin America (Yap 1994).

Rice production increase by expansion of rice areas is only projected in some developing countries, particularly Africa. Therefore production should be increased by increasing the yield per unit area, and adapting highly productive and environmentally viable cropping technologies.

As Shastry *et al.* (1994) stated, with growing demand for rice which is staple food and with limited opportunities to open up new areas, it has become necessary for many developing countries to adopt the intensive crop management with the high yielding and fertiliser responsive varieties (HYVs), a movement popularly referred to as the green revolution. Yields of intensive rice production have been plateauing and the resource base supporting rice production has shown signs of accumulated stresses. Concerns about changes in the status of rice pests and diseases, negative impacts on the environment and losses of natural resources and biodiversity have increased. In Asia during the past decade, rice paddy areas in most of major rice producing countries have remained static or even declined.

Weeds are, without any doubt, a major pest and constraint to increasing rice production. Weeds interfere with rice growth in different ways: a) by competing for light, nutrients and water; b) living or decaying weeds can secrete toxic root exudates or leaf leachates which depress the normal growth of the rice plant; c) high weed density creates a habitat for growth of various pest organisms (insects, nematodes and pathogens) which adversely affect rice production; d) weeds demand high labour inputs for control, i.e. nearly 30% of the required labour; and huge crop losses may take place in rice fields with high weed infestations which prevent normal harvesting operations.

Weed control is carried out through the implementation of various control methods, among them land preparation. Improved land preparation should serve to reduce weed density, but also to

prevent soil erosion and to conserve water, particularly in upland rice. Therefore weed management practices should be fully compatible with water and soil conservation procedures.

Besides that it is well known that weeds are a gender issue: many women and children spend considerable labour time in weeding, and rice crops are no exception. Improved weed management should aim to reduce labour inputs for weed control in general.

The use of herbicides rapidly developed in rice shortly after World War II and many people believed that herbicide application would be the main solution to weed control in this crop. Life has shown that although herbicide use has increased productivity there are still several weed problems unsolved by herbicides commonly applied in rice.

The shift of rice production from transplanting to direct-seeding has led to the predominance of various difficult to control weeds, many of them closely related in biology and morphology to rice, such as red rice weed. Weed species of the *Echinochloa* complex are still a major problem in nearly all rice producing countries, herbicide applications do not always reach the required control level for these weeds and certain species are becoming resistant to currently used compounds.

In addition, many farmers spray herbicides without any knowledge of time of application, correct dosage and safety measures, they also lack machinery and properly maintained spraying nozzles. The sum of all this reduces rice yields, pollutes water, soil and surrounding wildlife.

The integrated weed management approach is an urgent requirement for improvement of rice production. It is not possible to expect efficient weed control solely by practising chemical control. Various preventive, cultural, physical, chemical and, perhaps, biological methods should be rationally integrated to achieve the desired weed control. Integrated weed control methods should reduce the actual production cost and minimise environmental pollution.

In the concluding session of the first International Conference on "Temperate Rice-Achievements and Potential", held at Leeton/Yanco, New South Wales, Australia, 21-24 February 1994, the participants of this event agreed to give more research efforts to various problems, among them weed management.

Considering the importance of rice production in developing countries FAO has decided to publish this volume which gathers valuable information regarding current weed control practices in different regions of the world, describes their advantages and shortcomings, and recommends ways for further improvement.

This book can be used by agricultural researchers and extensionists as a guide for weed management in rice, as well as a tool for training agricultural technicians in integrated weed management procedures.

FAO is greatly appreciative of various weed scientists from all over the world for their kind and valuable technical contributions and, in particular, to the editors, Dr B. Auld and Dr K.U. Kim for their patience and dedication to edit this book.

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CHAPTER 2
BIOLOGY OF PADDY WEEDS

BIOLOGY OF PADDY WEEDS

K. U. Kim and K. H. Park

INTRODUCTION

The biology of weeds is concerned with their establishment, growth and reproduction. Environmental factors have a remarkable impact on all these processes. The most important factors governing life of species are heredity and environment. Heredity determines growth potential, reproductive methods, and life span. The environment determines the extent to which these processes proceed (Ashton and Monaco 1991).

The distribution of weeds in paddy fields is largely determined by environmental factors modified by competition from the rice. Cultural practices also play an important role in determining whether a weed species reaches a given area. Many weeds have a wide environmental tolerance and a broad geographical distribution; some species occur in man-made habitats far outside their normal range.

Weeds usually emerge faster than the rice plant, absorb available water and nutrients earlier, establish their growth earlier and suppress rice growth. In general, an effective weed control in the rice fields can be made on the basis of a comprehensive knowledge of the biology, ecology and ecophysiology of weeds. In tropical Asian countries, moderate year-round warm temperature and high humidity encourage year-round growth of weeds. On the other hand, many weeds occur in temperate countries in association with high temperatures and high humidity during the summer rice growing season.

Understanding the biological and ecological characteristics of weeds, with emphasis on their reproductive potential and competitive ability is a key to establish an effective control methods. This chapter attempts to help people identify and understand major weeds in rice paddy fields in tropical and temperate countries.

BIOLOGY OF THE MOST IMPORTANT PADDY WEEDS

Tropical Areas

***Echinochloa crus-galli* (L.) Beauv.** This weed is commonly associated with rice. Asia is considered its origin and it is now widely distributed in tropical and subtropical areas of the world. *E. crus-galli* is an erect, annual, up to 100-200 cm high. The stem is stout and spongy and the root is thick. Leaves are up to 40 cm long and 5-15 mm wide. The inflorescence is pinkish to purplish occasionally with green spikelets; lowest branches, the longest, occasionally to 10 cm long, often rebranched and spread at maturity; spikelets more or less elliptical, pointed, 3-3.5 mm long, usually slightly hairy; awns, if present, usually reddish or purplish, 2-5 mm long. The fruit is a caryopsis about 2 mm long. This weed is propagated by seed and adapted to wet soils. Seed may remain dormant for 3-4 months. *E. crus-galli* grows well at soil moisture of 80% water-holding capacity and optimum germination occurs at 70-90% of water-holding capacity. Seeds can also germinate under water. The growth of this weed becomes increasingly poor with increased depth of submergence. One plant may produce 40,000 seeds. Tillers profusely germinate throughout the year. This weed is ecologically similar to rice. During the

early vegetative phase, it can be distinguishable from the rice plants by its ligule. This weed is very competitive in rice and can reduce yields to zero. The major distinguishing characters between *E. crus-galli* and *E. colona* are presented in Table 1.

Table 1. The major distinguishing characters between two *Echinochloa* species.

Characters	<i>E. crus-galli</i> Beauv.	<i>E. colona</i> (L.) Link
Panicle	Usually nodding	Erect
Rachilla	Rather close on a rachis, more or less branched	Rather distant on a rachis, simple
Spikelet	Often not arranged in rows	Usually arranged in 4 rows
Awn	Variable in length	Awnless
Stigma colour	White or red	Blackish-purple
Anther colour	Brown or yellow	Purple



Mature plant of *Echinochloa crus-galli*

***Echinochloa colona* (L.) Link.** is a smooth, tufted annual 30-75 cm high, usually decumbent and rooting at the lower nodes, green to purple with an inflorescence of short spikes in an alternate arrangement on the main axis. The stem is flattened, often red-purple at the base, usually swollen at the nodes. Leaf sheath is smooth, margins free in upper part and basal portion of sheath is often tinged with red. Leaf blade is smooth, flat, linear-lanceolate, flaccid, up to 25 cm long, 3-7 mm wide, sometimes transverse purple bands. The inflorescence of *E. colona* is green to purple, ascending panicle, 6-12 cm long with 4-8 simple, short, compact branches 1-3 cm long, 3-4 mm wide, ascending or appressed about half their own length apart. Spikelets are ovate to broad ovate, acute, 2-3 mm long and crowded into 4 rows along one side of the branch, nearly sessile. Fruit, a caryopsis about 1.3-2 mm long. This weed is propagated by seed. In the tropics, seed has little or no dormancy and germinates throughout the year when moisture is available. *E. colona* normally grows under dryland conditions ; does not thrive in continuously flooded soils. Like *E. crus-galli*, young plants resemble rice, which makes hand weeding difficult early.

***Monochoria vaginalis* (Burm. f.) Presl.** is a semi-aquatic, broadleaf, monocotyledonous, annual weed, 10-50 cm high and the stem is usually inconspicuous and obliquely erect. Leaves are 2-12.5 cm long and 0.5-10 cm wide, oblong-ovate to broadly ovate, sharply acuminate, a heart-shaped or rounded, shiny, deep green in color, with longitudinal veins, petioles soft, hollow, 10-20 cm long, growing from buds at the base. The leaf sheath is twisted together at the base. The inflorescence is basally opposite the flowers arising as a 3-6 cm spike from a thickened bundle, two-thirds of the way up the petiole; pedicels 4-25 mm long. The fruit is a capsule, about 1 cm long, splitting into 3 valves.



Mature plant of *Monochoria vaginalis*

***Paspalum distichum* L.** is an erect or ascending perennial grass, with slender rhizomes and extensive stolons forming thick mats. The stem is much-branched, horizontal, giving rise to secondary roots. Leaves are flat or folded, 3-12 cm long, 2-6 mm wide usually hairy on the basal margins, sheaths loose, keeled, finely hairy towards the top and ligule 0.75-1.25 mm long. This weed has 2 (rarely 1 or 3) terminal erect to spreading spike-like racemes, up to 7.5 cm long, each bearing usually solitary greenish to yellowish spikelets in 2 rows along one side. The spikelets are appressed, elliptical and the upper glume hairy. The fruit is a brownish caryopsis. It propagates mainly by creeping stolons and to some extent, by seed. This weed is found in damp or wet situations, in wetland rice and dryland field crops and vegetables planted in banded fields. It is difficult to control because the detached stolon fragments regenerate easily and are tolerant of many herbicides.



Mature plant of *Paspalum distichum*

***Sphenoclea zeylanica* Gaertn.** is an erect, aquatic annual broadleaf that grows to 30-150 cm. The stem is smooth, stout, fleshy, hollow and much-branched. Leaves are simple, spirally arranged, oblong to lanceolate up to 10 cm long, 3 cm wide, narrowed to a point at the tip with a short stalk and entire margins. The inflorescence has green, cylindrical, dense terminal spikes, up to 7.5 cm long, 12 mm wide on a stalk up to 8 cm in length. Flowers are sessile, densely crowded, white to greenish and it is about 2.5 mm long and wide. Fruits are flattened, globular capsules, 4-5 mm across, splitting transversely. Seeds are numerous, yellowish-brown, 0-5 mm long. It is propagated by seed and grows in wet soils, preferring stagnant water.



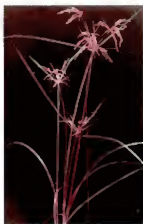
Mature plant of *Sphenoclea zeylanica*

***Fimbristylis littoralis* Gaud** (syn. *Fimbristylis miliacea* (L.) Vahl.) is an erect, annual tufted sedge that grows 20-60 cm high. The stem is flattened at the base, strongly 4-5 angled at the top, flowering stem 0.6-1.5 mm thick bearing 2-4 unequal bracts shorter than the inflorescence. Basal leaves have broadly overlapping leaf sheaths up to 35 mm long, 1-2.5 mm wide; stem leaves have very short blades. The inflorescence is a rather diffuse umbel, 6-10 cm long, 2.5-8 cm wide, spikelets numerous, solitary brown or straw-coloured, 2-2.5 mm in diameter. The fruit is a pale ivory to brown achene, 3-angled, 0.5-1 mm long, 0.75 mm wide, three heavy ridges on each side. This weed is propagated by seed and adapted to moist soils and areas of occasional flooding. It does not establish in submerged soils.



Mature plant of *Fimbristylis littoralis*

***Cyperus iria* L.** is a smooth, tufted, annual sedge that grows to 60 cm. The stem is sharply triangular. The root is yellowish-red, fibrous. Leaves have sheaths enveloping the stem at the base, membranous, with blade linear, lanceolate, shorter than the flowering stem, about 5 mm wide. The inflorescence is a compound umbel, with primary rays about 10 cm long, secondary rays about 2 cm long, subtended by 3-5 (occasionally 7) bracts. The fruit has a yellowish-brown achene, obovate, triangular in cross-section, 1-1.5 mm long. This weed is propagated by seeds, which may be dormant but can germinate about 75 days after shedding. It grows well in moist to wet soil, in dryland annual crops and plantation crops. It is a prolific seed producer and spreads quickly.



Mature plant of *Cyperus iria*

Cyperus difformis L. is an erect, smooth, densely tufted annual sedge that can grow as tall as 75 cm. The stem is sharply triangular at the top; 1-4 mm thick. Roots are numerous, fibrous and reddish. There are 3-4 basal leaves, with tubular sheaths, united at the base, the lower ones are straw-coloured to brown. The blade is rather flaccid, linear, abruptly acuminate, smooth, usually shorter than the flowering stem, 10-40 cm long, 2-3 mm wide. The inflorescence is a dense, globose, simple or compound umbel, 5-15 mm in diameter, subtended by two to four (usually three) leaf-like bracts 15-30 cm long and 6 mm wide. Primary rays of the umbels are 2-4 cm long; secondary rays about 1 cm long, some sessile, some long peduncled. Fruits are brownish achenes, elliptical to slightly obovate, lightly pitted, about 0.6 mm long. This weed is normally propagated by seeds and adapted to moist lowland soils or flooded areas. It is a heavy seed producer and can complete one life cycle in about 30 days. Through high seed production and short life cycle, this weed can spread rapidly to become a dominant weed in a rice field.



Mature plant of *Cyperus difformis*

Ludwigia octovalvis (Jacq.) Raven. is a stout, coarse, sometimes woody bi-annual aquatic broadleaf shrub weed that can grow to 100 cm tall. Its stem is erect, much-branched, glabrous to densely hairy. Leaves are simple, alternate, lanceolate to ovate, 6-15 cm long, 4 cm wide. Inflorescence is a solitary, axillary, sessile; petals yellow, broadly ovate or cuneate, 1-1.5 cm long, 2-7 mm wide. The fruit is green or purplish, cylindrical to somewhat club-shaped, 4-celled, thin walled, 1.5-4.5 cm long, 2-8 mm wide with 8 ribs; several rows of seeds are in each cell. This weed is propagated by seeds, some of which germinate immediately in wet or flooded soils. It grows in wet and aquatic conditions and it is very competitive with rice.



Mature plant of *Ludwigia octovalvis*

***Pistia stratiotes* L.** is a free-floating, stoloniferous, monocotyledonous perennial with long feathery roots, bearing small plants (off-shoots) at the end of each stolon. Leaves are pale green, overlapping, wedge-shaped, succulent, up to 10 cm long and 5 cm wide, covered on both surfaces with numerous fine hairs, forming a rosette about 15 cm in diameter on a short stem axis. Older leaves have a conspicuous, ovoid swelling filled with spongy parenchyma on the lower surface. Prominent veins are arranged in a fan-like manner. The inflorescence is composed of inconspicuous flowers: small, green; surrounded by green tubular spathes arising in the leaf axis in the centre of the leaf whorl. Fruits are green berry-like, slimy, rupturing irregularly, containing 4-12 brown seeds. Seeds are oblong, tapering towards the apex, 2-2.5 mm long, with a thick regulose seed coat. This weed is propagated by seed and grows in wetland rice.



Mature plant of *Pistia stratiotes*

***Leptochloa chinensis* (L.) Nees.** is a strongly tufted annual grass which grows 30-120 cm high. The stem is slender or somewhat stout, erect or ascending from a branching base. Leaves are linear flat, acute, thin, membranous, rough on the upper surface, sometimes reddish or purplish, 10-30 cm long, 4-9 mm wide, ligule 1-2 mm long, deeply divided into hairlike segments. The inflorescence is a narrowly ovate panicle with the main axis 10-40 cm long, branches and simple, numerous, spreading, 5-15 cm long, spikelets 2-7 flowered, pedicels 0.5-0.75 mm long, appressed or erect, pale green or reddish. Fruit of this weed has a caryopsis, ellipsoid, 0.8 mm long. This weed is propagated by seed and grows commonly in wetland rice.



Mature plant of *Leptochloa chinensis*

Cyperus rotundus L. is an erect, rhizomatous, tuber-forming perennial sedge which can grow as tall as 75 cm. The stem is slender, three cornered, and tuberous at the base. Leaves are flat, gradually acuminate, dark green above, light green beneath, 2-6 mm wide, lower sheath reddish brown. The inflorescence is a simple or compound spike up to 15 by 10 cm, usually much smaller. Involucral bracts usually 2-4x as long as or overlapping the inflorescence, extending up to 30 cm. Primary rays 3 to 9, very unequal, obliquely erect to spreading, slender and up to 10 cm. Spikes are ovoid, loose to rather dense with a glabrous rachis. The spikelets are spicately arranged, linear acute, strongly compressed, with 10-40 flowers, sometimes strongly accrescent and may contain as many as 100 flowers. Seed is an achene, ovate or oblong-ovate, 1.5 mm long, 3 angled, blackish when ripe. This weed is propagated by rhizomes, tubers and seeds and grows in dryland field crops, plantation crops and vegetables.



Mature plant of *Cyperus rotundus*

Scirpus maritimus L. is an erect perennial sedge with stout, tuber-bearing rhizomes. The stem is slender, 3-angled, up to 1 m high and underground stems are 3-6 mm thick, black-brown terminated by a globose tuber, covered with blackish, thick, membranous scales. Stems grow rapidly during early rice growth and may severely shade semidwarf rice cultivars during the first 40 days and tubers have dormancy. Spikelets of this weed are 1 to many, ovate to cylindrical, 10-35 mm long, some or all sessile, often single or clustered, notched at the top, and the midvein extended into a curved awn 1-3 mm long. Fruit is an achene, obovate, 2.5-3.0 mm long, 2-2.5 mm wide. This weed is propagated by tubers and seeds and is very competitive in lowland rice. It is difficult to eradicate because of dormant tubers and buds.



Mature plant of *Scirpus maritimus*

Temperate Areas

***Echinochloa oryzicola* Ohwi and *Echinochloa crus-galli* P. Beauv.** These are erect annual grasses which grow 50-100 cm high, usually close-tufted, in wetland rice fields. These two species can be distinguished by the length of the first, lower, empty glume, being half to slightly more, than the length of the spikelet for *E. oryzicola* and one third to less than one half the length of the spikelet for *E. crus-galli* (Kim 1994a). The stem is stout, erect to decumbent, often branching from the base. The colour of stem is light green. Leaves are acuminate and leaf sheath is glabrous. The inflorescence is usually narrow pyramidal, 10-15 cm long. These weeds are propagated by seeds and grow in wetland rice. The seed of *E. oryzicola* has a strong shattering habit when mature. Just after removal from the panicle, they obtain primary dormancy and do not germinate even if suitable conditions occur. Seed dormancy is caused by the caryopsis itself and not glumes. Dormancy breaking is influenced by many factors such as temperature, soil moisture and gas. Optimum germination is at 30 to 35°C. The lower limit is 10 to 15 °C and higher limit is 45 °C.



Photo of *Echinochloa oryzicola*

***Monochoria vaginalis* (Burm. f.) Presl.** is an annual aquatic monocotyledonous plant. It grows as tall as 10-30 cm with a glabrous, shiny appearance. Stem is usually inconspicuous, obliquely erect. Leaves are narrow at the early stage and 6-8th leaves are oblong-ovate to broadly ovate, the base heart-shaped or rounded, shiny, deep green in colour. Flowers are basally opposite the sheath of the floral leaf, violet or lilac-blue. This weed is propagated by tiny seeds, which are oblong, about 1 mm long. The plant height, number of leaves and dry weight of *M. vaginalis* are greatly affected by the seeding time. Earlier seeding dates produce significantly greater plant height, more leaves and dry weight than those of later seeding dates. Earlier seeding dates result in earlier flowering, but the interval between dates of seeding and flowering decrease progressively as the seeding times are delayed (Park and Kim 1987).



Photo of *Monochoria vaginalis*

Eleocharis kuroguwai Ohwi. is an erect, tuber-forming perennial. Plant height, number of tillers and top fresh weight per m² are 50-90 cm, 500-875 and 175-750 g, respectively. *E. kuroguwai* flowers from August when it is planted in May at Suwon, Korea. The maximum percent sprouting of *E. kuroguwai* is less than 60% until 50 days after incubation. This means the tuber of *E. kuroguwai* has dormancy. This weed propagates only by vegetative propagules. It bears several lateral buds in addition to one apical bud. This apical bud is dominant over lateral buds, but if removed, the remaining lateral buds readily sprout. This weed forms tubers deep in the soil. These propagules die when the temperature falls below -5 to -7 °C and cannot survive under dry conditions. Vegetative propagules with a water content of about 70% die when their water content decreases to 30%. For sprouting of this weed, the minimum temperature is about 10 °C, the optimum temperature is 30-35 °C and the maximum temperature is 40-45 °C, respectively; the tuber can sprout even under upland soil moisture conditions.



Photo of *Eleocharis kuroguwai*

Sagittaria trifolia L. is a fleshy, broadleaf perennial weed, 70-90 cm high. Leaf shape is an arrow 25-45 cm long. The stem is obliquely erect. It is propagated by seeds and tubers. Seed have dormancy. Each tuber of *S. trifolia* has only one bud on the top and if this bud is removed, the plant withers. *S. trifolia* forms its tuber in a deep position in the soil and survives there for several years. The tubers germinate between 15-40 °C. The optimum temperature range for basal emergence is 25-30 °C.



Photo of *Sagittaria trifolia*

Sagittaria pygmaea Miq. is a fleshy, semiaquatic, broadleaf, perennial weed, 8-15 cm high, with a glabrous, shiny appearance. The stem is usually inconspicuous, obliquely erect. Leaves are 0.5-0.8 cm wide and 8-15 cm long, shiny, deep green in colour with longitudinal veins. This weed produces seeds and tubers and is mainly propagated by tubers. The inflorescence has 30-50 fruits per plant with 350-420 mg weight per 1000 seeds, 2.3-0.5 cm long. Flowers are white, whorled in threes in a raceme-like panicle inflorescence. *S. pygmaea* is one of the most dominant perennial weeds in paddy fields in temperate countries like Korea and Japan. The stage at which rice plants are most affected by this weed is from 31 to 37 days after transplanting (Lee and Guh 1982).



Photo of *Sagittaria pygmaea*

Cyperus serotinus Rottb. is an erect rhizomatous, tuber-forming perennial, 50-100 cm high. The inflorescence is a compound umbel supported by an involucre of leaves. The fruit is an achene. This weed reproduces mainly through tuber formation and rarely reproduces by seeds. The tuber is nondormant under low temperature conditions. Unlike other perennial weed species, this weed requires high oxygen for germination. Rhizomes produce more in high nitrogen concentrations while there is less production under low light.



Photo of *Cyperus serotinus*

***Ludwigia prostrata* Roxb.** is an erect annual broadleaf weed, up to 30-60 cm high. Stems are erect, smooth, many branched, and reddened, but are often tufted from base. Leaves are lanceolate and alternate, having in their axil small yellow sessile flowers. The stem colour is red. Leaf colour turns into red from green at the late growing stage. This weed is propagated by seeds, 0.9-1 mm long. Capsules are slender and cylindrical.



Photo of *Ludwigia prostrata*

***Potamogeton distinctus* Benn.** *P. distinctus* is a floating, fleshy, broadleaf perennial weed, with a glabrous, shiny appearance. An aquatic perennial that grows in rice paddies, ditches, canals, marshes and ponds; common throughout Korea. It propagates by rhizomes and seed, but it spreads mainly by fast growing rhizomes and multiplies mainly by excised stems and overwintering scale-buds, formed several per rhizome. It grows from May to October and flowers in July to August. Deep and/or prolonged flooding promote growth. It competes strongly with rice lowering yields and impeding water flow. It is rather difficult to control due to deep distribution of rhizomes in the soil and strong ability for regrowth. Stems are simple or short-branched. Floating leaves are long petioled, alternate, lance-oblong to lance-elliptic. Submerged leaves are short-petioled, alternate, pellucid and thin, linear-lanceolate. Elongated flower stalks bear densely flowered spikes borne axillary from the stipules of floating leaves.



Photo of *Potamogeton distinctus*

Aneilema japonica Kunth. is an erect, broadleaf annual weed, 20-40 cm high. This weed is creeping during early growth. Seedlings are difficult to distinguish from barnyardgrass but petioles and leaf tips are lanceolate. Leaf sheaths have hairs. Stem colour is dark purple violet. This weed is propagated by seeds.



Photo of *Aneilema japonica*

Scirpus juncoides Roxb. var. *hotarui* Ohwi. is an erect annual weed, 20-70 cm high. Seeds germinate at 13-14 °C but it cannot germinate under dryland conditions. It flowers at 40-50 days after germination and ripens 1 month after flowering. *S. juncoides* produces seed, 2.0-2.3 mm long, 1.6-1.7 mm wide and 0.8-0.9 mm thick and is propagated by seed. Seeds require light for germination. This weed is very difficult to distinguish from *Eleocharis kurogunwai* at the vegetative stage. Leaves have very short blades. The stem is flattened at the base, strongly angled at the top. The seed is normally germinated at 25-35 °C with percentage germination of 10-25%. This weed readily germinates at 1 cm water depth on 1-1.5 cm soil depth but there is no appreciable germination 3-5 cm soil depth (Guh and Huh 1986). This weed has dormancy which is broken by low temperature under moist conditions.



Photo of *Scirpus juncoides*

ECOLOGICAL ASPECTS

Dramatic changes in practices such as a switch from manual to chemical weed control, from conventional tillage to no-till, or from transplanted to direct seeded rice, can lead to weed species shifts or replacements (Weaver 1994). Intense use of herbicides in rice growing countries like Japan, Korea and Taiwan has created weed shifts from annuals to perennial weeds. However, the switch from transplanting to direct seeded rice leads to dominance of grass weeds, particularly *Echinochloa* spp. (Kim 1994b).

In 1971 in Korea, the dominant weed species in lowland rice fields was *Eleocharis acicularis* and then *Monochoria vaginalis* in 1981 and *Sagittaria trifolia* in 1990 (Kim 1993). The shift of dominant weed species in paddy fields has been mainly influenced by the herbicides applied, followed by changes in cultural practices, such as fertilizer and water management, change in rice variety and abandonment of the double cropping system.

Allelopathy.

Dilday *et al.* (1991) reported that 347 accessions from the USDA/ARS rice germplasm collection exhibited allelopathic activity to *Heteranthera limosa* (Sw.) Willd.. Fujii (1992) reported 189 rice cultivars for allelopathic activity using lettuce as the assay crop, and found distinct differences between cultivars. Improved japonica cultivars showed little allelopathic activity, but traditional javanica rice cultivars and red rice showed strong activity. Lin *et al.* (1993) found that six allelopathic rice lines reduced the dry weight of aquatic weeds from 93 to 99% compared with Rexmont, a cultivar having no allelopathic activity. Rice husks showed high potential for allelopathic activity to enable control of paddy weeds in Korea (Park *et al.* 1993).

It may not be possible to identify rice varieties with allelopathic properties against all rice weeds. However, allelopathic substances for such weeds may be produced by other plant species. Genes responsible for such allelochemicals may be transformed in to improved rice through genetic transformation (Khush 1994).

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CHAPTER 3

WEED CONTROL TECHNOLOGY AS A COMPONENT OF RICE PRODUCTION SYSTEMS

WEED CONTROL TECHNOLOGY AS A COMPONENT OF RICE PRODUCTION SYSTEMS

S. K. De Datta and Aurora M. Baltazar

INTRODUCTION

Rice is grown on 148 M ha in 111 countries in the world; most in Asia (90%) and the rest (10%) in the Americas, Africa, Australia and Europe (De Datta 1981). The wide variation in geographic, socio-economic, and agro-climatic conditions in these areas has produced an equally diverse and contrasting extremes of rice production and weed control technology ranging from purely manual methods in less than 1-ha land in Asia to high-energy input technology in 500-ha farms in the Americas. Although numerous factors influence weed control in these areas, the two most important factors are: 1) water management systems, and 2) planting or stand establishment method. These systems or practices largely determine the dominant weed or weed groups, the nature of rice-weed competition, and consequently, the nature of control methods and the extent to which these are practised.

A semi-aquatic annual grass, rice, thrives and yields best when flooded for two-thirds or all of its life cycle. Rice production systems are thus classified according to availability of water as: 1) irrigated, 2) rain-fed, 3) flood-prone or deepwater, 4) dryland or upland. According to establishment method, rice is either: 1) transplanted as 8 to 35-day old seedlings in puddled soil; 2) broadcast or drill-seeded into dry soil; or 3) broadcast as pregerminated seeds onto wet (puddled) soil.

Of the world's rice area, 53% is irrigated, 27% rain-fed, 8% deepwater, and 12% upland rice (Table 1). One-hundred percent of rice in U.S., Europe, and Australia is irrigated. In Asia, only half of the rice area is irrigated, the rest is rain-fed lowland and some is deepwater or upland areas. In Latin America and Africa, about half of the rice area is upland rice, a third is irrigated while the rest are rain-fed lowland or deepwater. Direct-seeding (dry or wet-seeding) is the only establishment method in the Americas, Africa, Australia, and Europe. In Asia, more than 90% of rice is transplanted, with a trend towards increasing use of wet-seeding.

Submergence, which suppresses weed growth and the use of seedlings which have a head-start over germinating weeds, provides irrigated transplanted rice with the greatest competitive edge over weeds compared with irrigated seeded rice, which emerges and grows at the same time as weeds. In seeded rice, absence of floodwater in dry-seeded or upland rice makes it less competitive than rain-fed or irrigated (seeded) rice. Among the rice ecosystems therefore, greatest weed pressure and competition occurs in upland rice than in dry- or wet-seeded irrigated or rain-fed lowland rice and least in irrigated or rain-fed lowland transplanted rice. Because of assured water supply, less weed competition and other favourable growing conditions, highest yields are obtained with irrigated (seeded or transplanted) rice. Lower yields are obtained with rain-fed rice because of uncontrolled water supply, weed competition, and other unfavourable growing conditions. Least favourable conditions, greatest weed competition, and highest risks are found in deepwater or upland rice; consequently, these rice systems provide the lowest yields (Table 2).

Unlike the breeding for new cultivars, application of fertiliser, or provision of optimal water supply, the best weed control can only prevent yield loss but can never raise yields beyond the potential set by the cultivar or by yield-increasing inputs (De Datta and Herdt 1983). Farmers

Table 1. Distribution of rice area according to water management regimes, 1991.

Region	Irrigated		Rainfed lowland		Flood prone (deepwater)		Upland (dryland)	
x 1000 ha								
Asia	73943	(55) ^a	38753	(29)	10016	(8)	10539	(8)
Latin America	2042	(33)	427	(7)	112	(2)	3686	(59)
Africa	1107	(17)	1373	(21)	1327	(20)	2800	(42)
USA	1113	(100)	0	(0)	0	(0)	0	(0)
Australia	89	(100)	0	(0)	0	(0)	0	(0)
Rest of World	912	(88)	0	(0)	0	(0)	0	(0)
World Total	79206	(53)	40553	(27)	11455	(8)	17152	(12)

^a Numbers in parenthesis indicate % of total rice area in the region.

(Source: Anon. 1993)

Table 2. Average yield of world's rice-growing areas, 1991.

Region	Average yield (t/ha)				Region average (t/ha)
	Irrigated	Rainfed	Floodprone	Upland	
Asia	4.9	2.3	1.5	1.1	3.6
Latin America	5.0	2.4	1.8	1.6	2.8
Africa	5.0	2.1	1.3	1.0	2.0
USA	6.3	-	-	-	6.3
Australia	8.2	-	-	-	8.2
Rest of World	4.9	-	-	1.0	4.4
World Average	4.9	2.3	1.5	1.2	3.5

(Source: Anon. 1993)

seem to adjust the intensity of weed control according to the potential productivity of the crop and apply more intensive weed control inputs where yields are high. The yield potential then and not the intensity of weed pressure, determines the degree of weed control inputs applied into the various rice ecosystems. Thus, maximum input, including those related to weed control, are applied into irrigated rice and less input into rain-fed lowland, deepwater or upland rice. In

Asia, greatest weed control inputs are applied into irrigated transplanted rice than in direct seeded rice (which is either rain-fed or irrigated), while negligible or no weed control input is applied in deepwater or upland rice. This, in spite of the fact that rain-fed and upland rice, which incur greatest weed problems, need the most input in terms of weed control.

During a rice-growing season, non-synchronous germination of large reserves of viable weed seeds in the soil provides a continuous supply of competing weeds that pose a threat to a successful rice crop. Grasses are usually the first group that emerges and grows with rice, which coincides with the critical stages of competition. This consists of several flushes or regrowth of the same (grass) species or of another grass once the first is controlled. Broadleaf weeds and sedges emerge and grow later. Thus, three kinds of weeds (grass, broadleaf, sedge) pose control problems throughout the growing season. Because rice is a grass, its fiercest competitors are the grass weeds, with barnyard grass (*Echinochloa* spp.) as its recognised worldwide worst weed. Similarities in morphology, physiology, and growth habits pose a double-edged control problem in terms of stiffer competition for the same growth and development requirements and of similar vulnerable stages to control (germination to four-leaf stages) resulting in narrow margin of selectivity where post-emergence control measures are used. Thus, it is no surprise that weeds and weed control technology have played a major role in the history and evolution of rice production and culture.

Rice and its culture as a food crop originated in Asia, where to this date, it practically comprises the whole of the people's diet, nearly all of their agriculture, and much of their hopes (De Datta 1981). It was first grown as an upland crop in the upland regions of tropical Asia and as a lowland (flooded) crop in China (Chang 1976). Lowland culture gradually dominated upland culture because slash and burn methods of upland culture were not effective in controlling weeds in the tropics and higher productivity resulted from lowland culture (Chang 1976). The basic elements of lowland culture that were developed and perfected in China - puddling and flooding, and transplanting - were practices that facilitated the control of weeds. Both operations became integral parts of rice farming and remain widely practised to this day. To date, practically all of the rice (>90%) in Asia is transplanted and grown in flooded soil. In early times, weeding during the vegetative growth stage (after transplanting) was not practised intensively. Only a modest amount of weeding labour, if any, was provided by the family.

In the 1960s, the introduction of the Green Revolution brought with it the use of fertiliser - responsive, high-yielding, semi-dwarf cultivars. While this resulted in tremendous advances in productivity and doubled rice yields, it brought significant changes in weed management perspectives and practices. Increased fertiliser application enhanced rice as well as weed growth. The short semi-dwarfs with erect tillers were less competitive with weeds, especially tall, fast-growing grasses, than the tall traditional cultivars with droopy leaves which can form a canopy and shade out the weeds. Thus, the new technology brought about rice production practices that also intensified weed pressure and competition. The two traditional indirect weed control methods of transplanting and flooding were no longer adequate and more intensive direct weed control inputs were required.

Current weed management technology consists of direct cultural, chemical, and some biological methods and indirect cultural and agro-ecological methods. The indirect methods are actually crop production practices which supplement direct methods by providing optimum rice growth to enable rice to out-compete weeds. The overall objective of indirect control inputs is to reduce the degree of direct control inputs. The most important of these are land preparation, fertiliser

management and water management. Plant spacing or seeding rate, crop rotation, cultivar used, and preventive practices are also important. Unlike insects and diseases, weeds being plants, are affected by rice production practices in the same way; this can be manipulated to tip the balance in favour of rice against weeds. Unfortunately, also because many weeds have almost identical growth habits and growth requirements, practices which benefit rice will also benefit weeds while practices which harm weeds will also harm rice. Some growers opt for practices that favour rice then perform direct control measures on the weeds. But with proper management, certain rice cultural and production practices can be manipulated to make growing conditions more favourable to rice and less favourable to weeds.

The discussions in this chapter highlight the principles and practices involving direct and indirect weed control in rice culture systems in a worldwide perspective. Details of these practices for a particular country or region are found in the other chapters.

WEED CONTROL METHODS

Indirect Methods

Land preparation/tillage. Tillage operations include ploughing, discing, harrowing, soil puddling, and land levelling. Thorough land preparation using these tillage operations contributes to reduced weed growth by: 1) providing weed-free conditions at planting; 2) allows optimal germination, emergence and growth of rice seedlings and good rice stands; 3) provides level land which is extremely important for good drainage; and 4) suppresses growth of certain perennial weeds. Land preparation is a frequently overlooked crop production practice of indirectly controlling weeds. While it does not totally eliminate the need for direct weed control, it helps reduce subsequent weed growth and post-planting weed control inputs. Decreased weed weights have been directly correlated with increased number of ploughings or harrowings (Barker 1970), with deeper ploughing (Kusanagi 1977), or with puddling (Moody and De Datta 1982).

In developed countries, tillage is done with heavy equipment and sophisticated machinery to ensure thorough land preparation. In contrast, animal-drawn implements or engine-powered hand-pushed tractors in small farms in developing countries result in poorly prepared fields. Land preparation also varies among the rice-growing countries, depending on planting method and water management. These are classified broadly as wetland, dryland or limited tillage (De Datta 1981).

In temperate Asia where transplanting is usual and in tropical Asia where transplanting and wet-seeding are practised, wetland tillage is the most common method of land preparation. It involves: 1) ploughing and puddling by flooding fields for about 7 days; 2) ploughing at 10 to 20 cm depth to bury weed seeds, weeds and rice stubbles; 3) harrowing to break-up big clods two to three times at 7 to 10-day intervals; and 4) levelling the fields (Ampong-Nyarko and De Datta 1991). Puddling reduces soil percolation and water loss, provides ease of transplanting and hastens establishment and tillering of young transplants to enhance vigorous growth and competitive ability against weeds.

In dry-seeded rice areas like the U.S.A., southern Australia, most of Latin America and West Africa, parts of tropical Asia and most of Europe, dryland tillage is the most common method of land preparation. Dryland tillage involves one to two ploughings or discing 10 to 20 cm. deep followed by two to three harrowings with a spike-tooth or disc-harrow, and sometimes a roller-packer to break-up big clods, and then by land levelling (Anon. 1990).

Limited tillage involves elimination of one or two pre-planting operations (minimum tillage) or zero tillage. Limited tillage offers certain advantages in terms of soil conservation and savings in labour, water, power and capital. Where perennial weeds are not a problem, limited tillage may be practical for use in both dryland and wetland rice. In Arkansas, zero or minimum tillage reduced infestations of certain aquatic weeds like ducksalad (*Heteranthera limosa* (Sw.) Willd.) and reduced land preparation costs (Smith *et al.* 1993b). Herbicide use is an integral part of a limited tillage system; replacing tillage operations. If inappropriate herbicides are used, perennial weed problems can increase over time. In the tropics, certain perennial weeds are not adequately controlled and limited tillage is not practical (Ampong-Nyarko and De Datta 1991).

In the tropics, tillage during the dry season desiccates underground vegetative propagules and is an effective way to control certain perennial grasses like *Paspalum distichum* L., *Cynodon dactylon* (L.) Pers., *Oryza longisteminata* and *Imperata cylindrica* (L.) Beauv. In temperate areas, tubers and rhizomes brought to the soil surface are killed during the cold, dry periods. *P. distichum* is one of the perennial grasses in the tropics which is effectively controlled by tillage. This weed, which is not a serious problem where there is good tillage and water management, was observed to increase in dominance over the years due to poor land preparation or zero tillage (De Datta 1977; 1981). In long-term studies in the tropics *P. distichum* stands were shown to decline significantly as tillage increased from zero to one or more ploughings and harrowings (Bernasor and De Datta 1988).

In addition to ploughing and harrowing, land levelling as a tillage operation is extremely important to provide good drainage. In an uneven field, weed problems occur because of poor rice establishment in low spots and enhanced weed growth in high spots. In the U.S.A., precision-levelling has greatly facilitated water management and is considered second only to introduction of semi-dwarf cultivars as contributing to increased yields (Anon. 1993). Fifty percent (in southern U.S.A.) to 100% (in California) of U.S. rice fields are precision-levelled by laser-guided machinery. In Asia, engine-powered hand- pushed rototillers do not provide as precisely-levelled fields. In the absence of precise land levelling, farmers in Asia dig shallow ditches to drain excess water (Takashima 1984).

Seeding should be done immediately following the last tillage operation to give rice an equal start with weeds. In areas with poor irrigation facilities, seeding could be delayed by as much as 10 days after land preparation because of limited water supply (Baki and Azmi 1992). The delay between the last tillage operation and seeding or transplanting should be as short as possible to prevent weeds gaining a head start over rice.

Water management. Water is an essential requirement for optimum rice growth. Since ancient times, water has been an integral part of rice production and weed management systems. Rice cultures are defined by the water management system. Water supply comes from irrigation, rainfall, or both. Where irrigation facilities and/or water supply is adequate, the duration and depth of flooding can be managed to suppress weed growth. When combined with direct weed control methods, water management as part of an integrated weed management system is cost-effective and can give considerable savings in production costs. Most of the developed rice-growing countries like the U.S.A., Australia, Europe, and East Asia have adequate irrigation facilities and good water control such that water can be manipulated precisely during the growing season. This is not easily done in areas where irrigation facilities are inadequate, water control is poor and where water supply depends partially, or totally, on rainfall.

Most, if not all weeds, have an optimum soil moisture level below or above which growth is suppressed; hence, the time, duration and depth of flooding can be managed to suppress weed growth. Weed populations decrease with increase in water depth; levels as low as 2.5 cm have been shown to suppress weed growth markedly (Mabbayad 1967). Flooding at early rice growth stages will control young weed seedlings but as weeds become larger and well-established, controlling them through water management is more difficult.

Nishida and Kasahara (1975) observed that C_4 plants like *Echinochloa* spp. are dominant in upland conditions while C_3 plants like *M. vaginalis* and *C. difformis* are dominant in submerged conditions. Thus, many of the non-aquatic grasses, particularly *E. crus-galli*, do not survive in submerged conditions while many aquatic broadleaf weeds and sedges do not survive in upland conditions. This is also probably the reason why grasses are the first to emerge in a cropping season when there is still low moisture or submergence, while broadleaves and sedges emerge later when the field has been submerged for quite sometime. Grass weeds can therefore be largely eliminated by continuous flooding at 15 to 20 cm depth maintained throughout rice growth. Aquatic broadleaf weeds like *M. vaginalis* become dominant in continuous flood and are suppressed at saturation or field capacity (Moody 1991). Draining will dry out and kill aquatic weeds. *Pistia stratiotes* L., an aquatic broadleaf is killed by intermittent flooding and draining (De Datta and Jereza 1977).

The dominant weeds and resulting weed control practices can be traced to the water management system associated with a particular rice culture. This is best exemplified by dry-seeding in the southern U.S.A. and water-seeding in California. In California, severe infestations of grass weeds, notably *E. crus-galli* and red rice and limited herbicide alternatives for grass control due to regulatory restrictions or poor herbicide selectivity in water seeded rice, have led to widespread adoption of water-seeded rice to help control grass weeds. Water-seeding, "pinpoint flooding" and continuous flood, which has been the only water management system since 1920s, has resulted in the dominance of aquatic weeds *Ammania coccinea* Rottb., *Bacopa rotundifolia* (Michx.) Wettst. and *Sagittaria montevidensis* (Cham. & Schlect.) (Barrett and Seaman 1980) and from small-seeded *E. crus-galli* to large-seeded *E. oryzoides* (Ard.) Fritsch and *E. phyllopogon* (Stapf) Koss. which thrive in deep flooding (Barrett and Seaman 1980). To control the aquatic broadleaf weeds, MCPA, bentazon, and most recently, bensulfuron-methyl were used. The most recent consequence of this practice is the development of resistance of *S. montevidensis* and *Cyperus difformis* L. to bensulfuron-methyl after continuous use of this herbicide since 1988 (Hill and Hawkins 1994) (see Chapter 13).

In contrast, dry-seeding is the main practice in southern U.S.A. because of the availability of herbicide choices for grass control particularly after the introduction of propanil, molinate, and thiobencarb since the 1960s. Dry-seeding, flushing, draining and reflooding fields after seeding for good rice stands also encourages growth of grasses like *E. crus-galli*, *Leptochloa fascicularis* (Lam.) Gray, and red rice, and some broadleaves like *Aeschynomene virginica* (L.) B.S.P. and *Sesbania exaltata* (Raf.) Cory.

Aquatic weed problems, however, are not as severe in dry-seeded rice as in water-seeded rice (Smith *et al.* 1977). Continuous use of propanil for more than 20 years for grass control has resulted in the development of a propanil-tolerant biotype of barnyard grass (Baltazar and Smith 1994).

In temperate and tropical Asia, continuous flooding is maintained throughout the growth of transplanted rice: the dominant rice culture. Adequate irrigation facilities and good water control are available in temperate east Asia, where 93% of rice is irrigated. In south and south-east Asia, only 40% of rice is irrigated due to inadequate irrigation infrastructure and poor water supply. More than half of rice in south and south-east Asia, west Africa and Latin America is rain-fed. In addition to transplanted rice, dry-seeded or wet-seeded rice and upland rice are usually grown in rain-fed areas. In some of these areas, partial irrigation may be available. But for most of these, rainfall dictates the rice growing season, in contrast to fully irrigated rice in temperate countries, where the growing season is determined by temperature.

Drought and floods are the two most prominent production constraints in rain-fed lowland and upland rice because of extremely uneven rainfall distribution and poor water control. In a climate where 30 to 50% of annual rainfall can occur in a few days or weeks, control and use of this water is usually impossible (De Datta 1981) and the result is extreme moisture fluctuation from drought to flood in the course of a growing season. Rice and weed growth and efficacy of weed control methods are affected by variation in soil moisture. In most studies in the tropics, soil moisture (or lack of it) has been implicated as the single most critical factor, perhaps even more than fertiliser effects, to affect weed control practices. Weeding by hand or by rotary weeder is difficult if the soil is too dry or too wet. Herbicide activity increases with soil moisture content and optimum activity requires optimum soil moisture. In extremely dry soil, low herbicide activity can result in weed control failure (Jikihara and Kimura 1977; Janiya and Moody 1984). At the other extreme, excessive moisture will cause rice injury or even crop kill (De Datta 1980; Bernasor and De Datta 1983). Poor crop stand and herbicide injury due to excessive or unexpected rainfall at planting or at herbicide treatment are two major constraints to widespread adoption of wet-seeded rice (Moody 1992).

Fertiliser management. Efficient fertiliser management became more critical with the introduction of high-yielding modern cultivars because they require more fertiliser inputs than traditional cultivars and because of enhanced weed growth when fertiliser is applied. Nitrogen promotes rapid vegetative growth which produces a canopy to shade out and suppress late-germinating weeds. Phosphorus increases tillering and root development for increased moisture and nutrient absorption. These properties enhance the ability of rice to compete with weeds and complement direct weed control measures. If not properly managed, however, rice may suffer greater weed competition from fertiliser application than when there is no fertiliser.

Proper management ensures fertiliser use by the crop at critical growth stages when fertiliser is most needed. Inefficient plant recovery of N is the largest constraint to high agronomic efficiency. Recovery of N fertiliser applied to the rice crop averages 30 to 40% and seldom exceeds 60 to 65% even with the best agronomic practices (De Datta *et al.* 1968). With an uptake efficiency of 36 to 50%, 100 to 150 kg/ha N is required to obtain a yield of 6 t/ha. In a rice-weed mixture, Ampong-Nyarko and De Datta (1991) determined that 75 to 100 kg/ha N gave optimum dry matter of rice. In most irrigated rice areas in Asia, 60 to 90 kg/ha N is applied in the wet season, and 100 to 150 kg/ha N is applied in the dry season (Anon. 1993). Much higher rates, from 120 to 180 kg/ha N, are applied in direct-seeded rice in the U.S.A. (Anon. 1990).

Poor crop and weed management and neglect of timely N application are the two most important factors contributing to low N use efficiency in irrigated rice systems. Usually, two to three split applications: at seeding/transplanting; at tillering; and at panicle initiation are needed to achieve

an N supply that is synchronous with the rice growth requirements (De Datta 1981). This is where weed management plays a critical role in achieving efficient fertiliser use. Because of their greater ability than rice to compete for N, weeds absorb fertiliser faster than rice. Even the maximum amount of fertiliser is of little significance if weeds are not adequately controlled before fertiliser is applied. Timing of N fertiliser should then be managed such that maximum benefit goes to rice and not to weeds. If shaded by fast growing weeds, rice shows little or no response to N application (Ampong-Nyarko and De Datta 1993).

If weeds are adequately controlled, N can be applied anytime between seeding or transplanting and the onset of the reproductive stage of rice. With adequate weed control for most rice cultures worldwide, the common practice is to split N into two or three applications, with 1/3 to 2/3 of total N at the first application and the remainder during the second and third applications. In Asia, the recommended times are: at transplanting or seeding, at 25 to 30 days after seeding or transplanting after crop has been weeded; and at 5 to 7 days before panicle initiation (Nantasomsaran and De Datta 1988; Bernasor and De Datta 1993). Minor variations may be needed with certain cultivars depending on growth duration, and among the different rice cultures.

A two- or three-split application is also practised in direct-seeded rice in temperate countries (Anon. 1990). The first dose of N is applied either at seeding (California) or at 4 to 6 weeks after rice emergence before application of permanent flood (southern U.S.A.) and the second dose is applied at mid-season. Depending on cultivar, the mid-season application is further split evenly at panicle initiation during internode elongation and 1 to 2 weeks later. In the southern U.S.A., the activity of certain herbicides may be affected by the first N application. This application timing coincides with application of fenoxaprop, a post-emergence grass herbicide which is applied to no younger than four-leaf rice for maximum selectivity. In cases of rainfall or low solar radiation, activity of fenoxaprop is enhanced if applied within 7 days of N application and flooding, which can result in moderate to severe rice injury (Smith *et al.* 1993a). To avoid or minimise rice injury under these conditions, fenoxaprop is best applied before N application and flooding; this is also the best option in terms of the need to control weeds before N is applied. However, if fenoxaprop application is delayed until after application of permanent flood, an interval of more than 7 days between fenoxaprop treatment and N application is needed to avoid rice injury (Smith *et al.* 1993a).

Basal application, top-dressing, and broadcasting by hand are the most common methods of application in Asia. In industrialised countries, Fertiliser is broadcast by aircraft into dry soil or into the floodwater. Research has shown that deep placement (10 cm depth) into the reduced soil layer is the most efficient method of fertiliser application in lowland rice (De Datta 1981). Broadcasting into non-flooded soil is more efficient than broadcasting into floodwater; both however are not as efficient as deep placement.

In cases of inadequate weed control, it is best not to apply N or to apply N at low levels. Another option is to apply N shortly before panicle initiation, or to delay application until the rate of N uptake by weeds has slowed down, which is usually after weeds have flowered (Matsunaka 1970). This should be easy because most of the major rice weeds flower much earlier (30-40 DAS) than do even medium-maturing cultivars (70-80 DAS). Increasing N level can not compensate for inadequate weed control. On the contrary, increased N enhances weed growth and results in greater competition and low rice yields than when there is little or no fertiliser. Rice and weeds showed similar rates of N uptake at 0 N and greater uptake by weeds

than by rice at 150 kg/ha N (Ampong-Nyarko and De Datta 1989). Thus at high fertiliser levels, weed control is more critical than at low N levels and it is not possible to produce high rice yields without adequate weed control.

Seeding rate/plant spacing. Seeding rate (direct seeded rice) and plant spacing (transplanted rice) determine rice stands or rice plant density per unit area. This in turn determines the amount of canopy developed to help rice shade and compete with weeds. Increased spacing between or within rows increases light penetration into the canopy which enhances weed growth. In addition, the optimum seeding rate or plant spacing essential for proper rice crop development and high grain yields also depends on cultivar, soil fertility, and cropping season. Proper seeding rate/ plant spacing should prevent weeds from occupying open spaces but not be too high so as to result in thick stands, lodging and intraspecific competition.

In situations where weed control inputs are not adequate, correct seeding rate or plant spacing can be critical. If weeds are adequately controlled, it is not necessary to use high seeding rates to suppress weed growth.

Weed weights have been shown to decrease correspondingly as seeding rates were increased from 50 to 250 kg/ha (Moody 1977a). Considering weed control, seed costs, and other cost-benefit factors, research has identified optimum seeding rates of 100 kg/ha in direct seeded rice (De Datta 1989) and plant spacing of 20 x 20 cm to 25 x 25 cm in transplanted rice (Kim and Moody 1980). Increasing seeding rates as high as 150 to 400 kg/ha will help control weeds in wet-seeded rice (Moody 1977a) but not in dry-seeded rice where weed pressure is much more intense and particularly if semi-dwarf cultivars are used (Moody 1982). In dry-seeded rice, high seeding rates cannot substitute for direct control measures. In direct-seeded rice in the U.S.A., the ideal seeding rate is about 100 seeds/m² which gives a desired plant density of about 50-60 plants/m² (Anon. 1990)

No weed control benefit is obtained when seeding rate is increased beyond the optimum 100 kg/ha that will give adequate crop stand establishment (Ampong-Nyarko and De Datta 1991). However, in some parts of tropical Asia, the Philippines, for instance, because farmers use their own seed source, they prefer using very high seeding rates (250-400 kg/ha) to compensate for pest damage such as birds, snails and rats and for potentially poor rice stands from unexpected floods.

Cultivar selection. Tall, fast and vigorous early vegetative growth, drooping leaves that form a canopy, vigorous root system for water and nutrient absorption and high tillering ability are traits which give rice an advantage when competing with weeds. In the past, tall, drooping-leaf traditional cultivars have a height advantage over broadleaf weeds and sedges, then the prevalent species infesting rice crops (De Datta 1980). But traditional cultivars are susceptible to lodging, have few tillers, and low yield potentials. In the search for high yielding traits during the Green Revolution, increasing the grain-straw ratio by breeding cultivars with short, sturdy-strawed culms and erect leaves that would resist lodging even with high rates of fertiliser was a major determinant to N responsiveness and high yields. With the introduction of the dwarfing gene, rice breeders and agronomists came up with 10 t/ha yielding cultivars starting with IR8 in 1966 (De Datta *et al.* 1966) and rice culture has never been the same since then. To date, the semi-dwarf plant type exemplified by IR8 with short stature (about 100 cm), sturdy culms, high tillering ability, lodging resistance, and dark green erect leaves represents the most efficient combination of rice traits essential to high fertiliser responsiveness and high grain yields. These

traits are in sharp contrast to those which favour weed competitiveness. However because competitiveness does not directly increase yields, rice scientists and growers have opted for high-yielding traits supplemented with direct weed control inputs. Throughout the rice-growing world, modern semi-dwarf cultivars were used, and their short stature and associated high fertiliser use highlighted the importance of adequate weed control to realize their full yield potential. Without adequate weed control, the semi-dwarfs are easily outgrown by tall, fast-growing grasses like *Echinochloa crus-galli* in flooded rice and *Rottboellia cochinchinensis* (Lour.) Clayton in upland rice. Introduction of direct-seeding further contributed to increased dominance of grasses; eventually grass weeds replaced broadleaf weeds and sedges as the prevalent species where semi-dwarfs are used in direct-seeded systems.

Increased adoption of direct-seeding in Asia and increased recognition of the need to reduce or integrate direct weed control methods with indirect methods in Integrated Weed Management (IWM) systems has renewed interest in the use of, and search for, weed-competitive cultivars. Since direct-seeded rice does not have the head start over weeds that transplanted rice does, use of cultivars that can emerge and grow fast within the first 30 days of seeding would enhance competitiveness of direct-seeded rice over grasses. Among existing modern cultivars, researchers have screened for, and identified, those which can compete best with weeds in their respective local growing conditions. In many rain-fed areas, direct-seeded growing rice cultivars with intermediate stature (about 120 cm) are preferred over shorter-statured cultivars. Intermediate or moderately tall rices are also more desirable for upland conditions (Chang *et al.* 1972). Consequently, intermediate stature and moderate tillering are being introduced into rices with erect leaves and sturdy culms (Khush and Coffman 1977). More recent research has identified weed-competitive traits like a vigorous root system and rapid early vegetative growth (Janiya and Moody 1993) in initial efforts towards possible future breeding programs designed to develop high-yielding as well as competitive cultivars.

Crop rotation. Each of the various rice systems is associated with a characteristic weed problem(s) and control practice(s) such as aquatic weeds in flooded rice and upland weeds in non-flooded rice. Repeated use of the same control methods due to mono-cropping on the same land year after year could lead to a build-up of weed populations not controlled by existing methods. This could result in either: 1) dominance of a difficult-to-control species or 2) in cases of repeated herbicide use, development of herbicide-resistant weeds. To prevent continuous use of control methods and to break the cycle of associated weeds, rice is rotated with crops having different growth habits or cultural requirements, for example flooded rice with an upland broadleaf crop.

Crop rotation is a common practice in rain-fed and upland areas where the rainfall pattern or inadequate irrigation requires planting of an upland crop during the dry season. In rain-fed areas in tropical Asia, rotating crops in rice-based systems is a common practice. Rice is grown in the wet season (June to November) and upland crops (vegetables or legumes) in the dry season (December to May). Aquatic weeds that thrive in flooded rice are dried out and killed during the dry season crop while upland weeds are submerged and killed when flooded rice is grown the following season. This rotation system decreased populations of *Scirpus maritimus* L., an aquatic weed which thrives in flooded rice in some countries in tropical Asia (De Datta and Jereza 1977; Bernasor and De Datta 1986).

Crop rotation is also practised to decrease weed populations even in irrigated areas where continuous rice crops can be grown once (temperate areas) to thrice a year where temperature

is not limiting. In the U.S.A., rice is commonly rotated with upland crops like soybean, sorghum or cotton every two years to reduce red rice populations (Smith 1976). In eastern Europe, a seven to eight-cycle crop rotation (rice followed by a different upland crop each year for 7 to 8 years) reduced aquatic weed populations by 80% (Podkin *et al.* 1983). In southern Europe, rice is grown 4 to 6 years, then upland crops for 1 to 3 years (Catizone 1983). Crop rotation in rice is not economically attractive and not very common in east Asia (Korea and Japan); use of a rotation crop depends on its market potential (Kim 1992).

Rotating rice with a broadleaf crop will also enable use of grass herbicides to control grass weeds which otherwise cannot be used in rice due to selectivity problems. In southern U.S.A., red rice is treated with a grass herbicide during the rotation crop of either soybean or grain sorghum (Smith 1989). Rotation of herbicides when crops are rotated also helps prevent buildup of weed tolerance or resistance and is one of the major management tools in preventing development of herbicide-resistant weeds (see Chapter 13).

However, crop rotation of a regular pattern (rice in wet season, vegetable crop in dry season) using the same practices every alternate season can have the same effect as monoculture and give rise to similar problems encountered in monoculture (Plucknett *et al.* 1977). Thus even with crop rotation, a change in crop and weed control practices every so many years is essential to avoid falling into a routine monoculture pattern.

Prevention. Preventive methods include all practices aimed at preventing weed and weed seed dispersal and build-up of seed reserves in the soil by: 1) use of weed-free seeds or weed seedling-free transplants; 2) maintenance of clean fields, borders, levees, and irrigation canals during the growing season as well as fallow periods; 3) screening weed seeds from irrigation water; 4) cleaning tillage and other farm equipment to prevent transfer of weed seed-contaminated soil from one field to another, and other similar sanitary measures. Preventive methods are also one of the most frequently overlooked indirect weed control measures, particularly the use of clean seed and maintenance of clean fields and surroundings during fallow periods.

If strictly observed and enforced, setting seed certification standards and enforcing regulatory measures for use of certified seeds can effectively decrease weed populations. In California, previously severe red rice infestations have been practically eradicated by growers' use of certified seed (Randall 1951). Use of clean certified seeds could be difficult to enforce in areas where farmers obtain their seed source from the previous harvest to lower production costs, as is commonly done in parts of tropical Asia. In transplanted rice, *E. crus-galli* seedlings which are difficult to distinguish from rice seedlings are mistakenly transplanted with rice.

In East Asia, farmers use non-selective herbicides (glyphosate, glufosinate, paraquat) or rotary weeder to control winter weeds before land preparation or weeds that grow after harvest during the autumn fallow (Kim 1992; Shibayama 1992). In Taiwan, farmers burn rice straw after harvest to control weeds and prevent build-up of weed seed reserves in the soil (Chiang 1992).

Direct Methods

Chemical control. The discovery of 2,4-D in the 1940s minimised the drudgery of hand or mechanical weeding. Since then, herbicides have been introduced which are efficient, practical and cost-effective particularly in areas where labour is scarce or expensive. They are often the best alternatives to control weeds in least amount of time and labour where vast areas are

involved. In the Americas, Australia, Europe and East Asia with vast rice areas and/or expensive labour, 90 to 100% of rice areas are treated with herbicide. Parts of south and south-east Asia and Latin America have moderate but fast-expanding herbicide use. Herbicide use increases with crop value; thus herbicides are most widely used in irrigated rice. In Asia, more herbicide is used in transplanted rice than in direct seeded rice and more herbicide is used in irrigated direct seeded rice than in rain-fed direct seeded rice. None or very little herbicide is used in rain-fed and upland rice in tropical Asia and Africa. Although weed problems are more severe, the area planted to upland rice is limited and grain yield is not as high as in irrigated rice.

Herbicides are applied into non-flooded soil or into the floodwater and require appropriate equipment and calibration. Improper calibration or application could result in underdosage and inadequate control or overdosage and rice injury and adverse effects on environment. Solid formulations like granules are broadcast manually or mechanically while liquids are sprayed with backpack- or tractor-mounted sprayers. In the Asian tropics, farmers broadcast granules manually and spray liquids with a hydraulic knapsack sprayer; CO₂-pressurised knapsack sprayers are rare for small farm use. In industrialised countries, herbicides are sprayed with tractor-mounted sprayers or by aircraft. In Japan, granules are the most widely used formulations; while liquids are preferred in other parts of Asia.

The specific herbicides used since 1940s and their general use patterns in the rice-growing world have been discussed elsewhere (Baltazar and De Datta 1992). In general, it involves treatments against predominant weeds at particular growth stages; grasses early in the season and broadleaf/sedge weeds later in the season. The first treatment is made pre-emergence to the weeds anytime shortly after the last tillage operation to shortly before or after seeding/transplanting. Pre-emergence treatments however control mostly annual grasses, have short residual activity, and are most effective only from germination to no-later than the one-leaf stage of weeds. In the case of regrowth, escapes, or new germinations, early post-emergence treatments are applied most effectively on one- to two-leaf weeds and no later than four-leaf stage of weeds. Early post-emergence treatments control grasses and/or broadleaf or sedge weeds. Depending on weed pressure or environmental conditions, only one application, either pre-emergence or early post-emergence, may be needed for adequate weed control at the early stages. Late post-emergence treatments are applied at four-leaf stage of weeds to control the aquatics (broadleaf and sedge weeds). New post-emergence grass herbicides are also now available for application to no younger than four-leaf rice and no later than early tillering grasses.

Until the 1970s the most widely used herbicides controlled annual species and were quite specific in application timing and weed spectrum: pre-emergence to grasses and post-emergence to broadleaf/sedge weeds. This practice of pre-emergence weed control resulted in two significant developments: 1) build-up of difficult-to-control perennial weeds, and 2) the need for two to three applications to control all kinds of weeds in a season (De Datta 1981; Kim 1994; Shibayama 1994). Herbicides developed from the 1980s have wider spectrum for annual and perennial weed control and wider application windows (pre-emergence to early tillering). Designed to control as wide spectrum as possible in a one-time application, these are popularly called "one-shot" treatments and are widely used in East Asia to save on labour and application costs. These new herbicides also have new chemistries, new modes of action, and much lower use rates than older compounds (De Datta and Baltazar 1994). However, those with single sites of action like the ALS inhibitors (sulfonylureas) and ACCase inhibitors (aryloxyphenoxypropionates) are resistance-prone and have started to pose resistance

management problems in certain rice-growing areas.

Herbicide selectivity plays a critical role in rice weed control. With most rice herbicides, rice may suffer no more than 30% initial injury of chlorosis and stunting which disappears within 2 to 4 weeks. Rice fully recovers and yields are not affected. Injury greater than 30% could occur under certain conditions, especially with grass herbicides. Most, if not all of the broadleaf/sedge herbicides have adequate physiological and morphological selectivity to rice. It is the grass herbicides which pose the greatest selectivity problems. Nearly all of the grass herbicides used in rice, except propanil, do not have adequate physiological selectivity. The next best alternative, morphological selectivity, is also difficult to obtain because of the close similarities between rice and grasses. The most vulnerable stages of grass weeds, one to four-leaf stages, are also the most vulnerable stages of rice. This is where transplanted rice, having bigger and older seedlings at the time of grass weed emergence, has an edge over direct seeded rice in terms of herbicide selectivity. Direct seeded rice, emerging and growing at the same time as grasses will have a narrower selectivity margin in age and size of seedlings. Pre-emergence herbicides applied to transplanted rice have widest selectivity while post-emergence herbicides in direct seeded rice have the least selectivity.

With pre-emergence (soil-applied) grass herbicides, adequate selectivity is obtained by timing herbicide application when the mesocotyl/coleoptile regions, the absorbing tissues of rice, have emerged above the soil surface or are away from the herbicide-treated layer (Chun and Moody 1985; Arceo and Mercado 1981). This is done by manipulating seeding/transplanting dates in relation to time of herbicide application. The safest times are at 2 days before seeding or not earlier than 6 days after seeding (Arceo and Mercado 1981). Some herbicides like butachlor and pretilachlor have safened formulations for use in direct seeded rice. Some rice cultivars may be more tolerant than others, depending on mesocotyl lengths (Chun and Moody 1985). The absorbing tissues of cultivars with short mesocotyls are more likely to be away from the herbicide layer and escape injury. Those with long mesocotyls have absorbing tissues nearer the soil surface and are more likely to be in contact with the herbicide layer. Absorbing tissues of grass weeds like barnyard grass are always close to the soil surface and herbicide layer (Baker 1960).

With post-emergence (foliar-applied) grass herbicides, only propanil has adequate physiological selectivity. Although it has the same target site (PS II inhibition) in rice and grasses, it is degraded by the rice enzyme arylacetylamidase (Matsunaka 1983). This enzyme is not present or not active in the grass weeds. Propanil should not be applied within 7 days of carbamate or organophosphate application. Being cholinesterase inhibitors, these compounds also inhibit arylacetylamidase and prevent propanil degradation and selectivity. Aryloxyphenoxypropionates (APPs) have the same target site (ACCase inhibition) in rice and grasses (Walker *et al.* 1989). Some degree of differential absorption, translocation, or degradation may occur, but not enough to account for adequate selectivity. Thus, treatments are fine-tuned to rates and times most selective to rice yet still provide adequate grass control (Baltazar *et al.* 1993a). Fenoxaprop, the most widely used APP for rice weed control, is applied to no younger than four-leaf rice and to no larger than four-leaf grass. Fine-tuning of most selective application rate and time is site-specific and depends on particular local conditions. In southern U.S.A. adequate grass control and minimum rice injury is obtained when fenoxaprop is applied to four-leaf rice and grass before, than after, permanent flooding (Smith *et al.* 1993a). In the Asian tropics, it is applied in flooded or non-flooded conditions to four- to five-leaf rice and grasses (Lourens *et al.* 1989).

Soil moisture is a highly critical factor affecting herbicide selectivity in rice because: 1) rice is grown in flooded soil throughout or most of the season; 2) a large part of the rice-growing areas are in tropical Asia where water control is aggravated by highly variable rainfall distribution leading to extreme variabilities in soil moisture which affect herbicide activity. Herbicides work best in optimum soil moisture, are inactive in extremely dry soil, and injure rice in extremely wet soil. In rice areas with good water control, desired moisture level for optimum herbicide activity is obtained by flushing or draining fields. Propanil, for example, needs uniform spray coverage because it is not translocated. Thus, leaf surfaces have to be exposed by draining before, and reflooding after, propanil application. This practice is not easily followed in the tropics. In dry-seeded rice in southern U.S.A. propanil is applied to two-leaf grass before permanent flooding and draining is not needed. Flushing may be needed when the soil is dry to activate propanil as well as weed growth.

Because of uncertainty of rainfall in rain-fed areas in the tropics most rice farmers hold as much water as they can on the fields by bunds or permanent levees. In case of a heavy downpour, the resulting water depth may submerge and kill rice seedlings (De Datta 1981). In wet-seeded rice, rainfall occurring at the time of herbicide application could result in severe injury to rice seedlings.

Rice injury from herbicides due to excessive moisture is not as serious in upland rice as it is in wet-seeded or flooded rice (Baltazar *et al.* 1993b). However, in dry-seeded or upland rice, low herbicide activity due to extremely dry soil at the time of herbicide application could result in poor weed control. For example, in rain-fed dry-seeded rice, several weeks may pass before there is sufficient rainfall to activate pre-emergence herbicides applied 3 to 4 days after seeding and for weed seeds to germinate. During that dry spell, the herbicide may have dissipated and weed control will be poorer than if rain had occurred earlier (Moody 1977b).

Cultural Methods. Direct cultural methods include removal of weeds by hand, with weeding tools (hoe, scythe, spade) or with mechanical implements.

Pulling weeds by hand is the surest way to control weeds and in older times was the only direct method of controlling weeds in rice. It takes from 200 to 500 man-hours, in two to three operations to weed 1 ha of rice by hand (Chan 1967; De Datta 1974). In an effort to reduce the hours spent in hand-weeding, research has shown that, if done at the right time, the number of hand-weedings that provide season-long weed control can be reduced to only one in transplanted rice, two in wet-seeded rice and three in dry-seeded lowland or upland rice. The critical times of weeding, beyond which more weeding hours and reduced grain yields occur, have also been identified by research to range from 21 to 42 days after transplanting (De Datta 1979) and from 15 to 40 days after dry- or wet-seeding (Moody and De Datta 1982).

In small-sized farms in tropical Asia or Africa, hand-weeding still remains a practical and cost-effective option in transplanted and drill-seeded rice where labour is free (family labour) or cheaper than herbicides. In broadcast-seeded rice, hand-weeding is not practical. Hand-weeding or mechanical weeding using hand or animal-drawn implements is still common as the only direct method in small farms in upland rice in tropical Asia and Africa, where herbicides are seldom used and if soil is too dry.

In most other rice-growing areas, increasing cost of labour compared with herbicides and/or its scarcity during critical periods are the major reasons that rice farmers use hand-weeding only

as a supplement to mechanical weeding or to herbicides. Hand-weeding enables removal of weeds close to, or along rice hills which are not removed by inter-row cultivation as well as removal of escapes, especially deep-rooted perennials, from herbicide treatment. One application of a pre-emergence or a post-emergence herbicide followed by one hand-weeding is probably the most widespread practice in small farms in tropical Asia, to reduce the time spent in weeding and in herbicide use. In east Asia and other industrialised countries, hand-weeding is done to remove escapes after herbicide treatment. It takes only about 30 to 40 h/ha to hand-weed escapes after herbicide application (Chiang 1981).

Mechanical weeding is done with human- or engine-powered inter-row cultivators or rotary weeders. It takes about 50 to 60 man-h to weed 1 ha of rice field by mechanical weeding (Parthasarathi and Negi 1977). Single-row rotary weeders take about 80 to 90 man-h to weed 1 ha. Thus, it is twice to several-fold more efficient than hand-weeding. But it is practical only in row-seeded rice and does not remove weeds within rows or close to the rice hills which can still cause marked reductions in yield (De Datta 1981). Push-type rotary weeders are difficult to use because they must be moved back and forth and do not work well if soil is too dry, if weeds are too big, or if floodwater is too deep (Moody 1991).

Rotary weeders are the most widespread used technique in Asia, either alone or combined with hand-weeding or herbicide. In Japan, engine-powered rotary weeders are used to control perennials which become dominant once annuals are controlled with herbicides. They are also used in autumn or winter between cropping seasons to expose and freeze underground propagules of perennial weeds (Shibayama 1992).

Biological Control. Control of weeds with biological agents such as insects or other natural enemies is a relatively new approach in rice weed control. Classical biocontrol is a slow process and has been most successful in situations involving long-term population dynamics of a single species in vast undisturbed non-crop areas. The feasibility of its widespread use in a mixed weed species flora is now being studied. The prerequisite of high specificity of a biocontrol agent (Hasan and Ayers 1990) limits its market potential and is an economic hindrance to its successful development (Templeton and Heiny 1989; Greaves and McQueen 1990). High specificity also means that the selective control of a single weed in a mixed rice-weed flora will not solve all of the rice weed problems. Biological control should thus be considered an added alternative, not a substitute, to other weed control methods (Watson 1992).

Use of herbivores as natural enemies of certain rice weeds may be considered the earliest form of biological weed control in rice. In the past, use of herbivores to control rice weeds have been limited to isolated small-sized farms in some countries in Asia (Matsunaka 1976). Recently there is renewed interest in studying herbivores for widespread use in Asia as well as in other countries. These include use of fish (red tilapia, grass carp) in Malaysia and Japan (Itoh 1991), tadpole shrimp, shellfish, ducks in Japan (Takahashi 1992; Shibayama 1992) and ducks for red rice control in U.S. and Latin America (Smith 1992). While herbivores are selective to older seedlings of transplant rice, they feed on young succulent seedlings of seeded rice. An example is the golden apple snail (*Pomacea canaliculata* Lamarck) which is now a serious rice pest in the Philippines (Basilio and Litsinger 1988).

To date, aquatic weeds of rice successfully controlled with classical biological control are *Salvinia molesta* and *Pistia stratiotes*. Rice weeds are not easy targets for classical biological control because more than 50% of the worst weeds in rice are grasses, and there is some concern

that a prospective agent will also feed on rice, other cereals or pasture grasses (Waterhouse 1992). Classical methods will probably be more successful in other rice areas outside of Asia, since it works best only on introduced (exotic) species, while most of the rice weeds are native to Asia. Of 61 species listed as major weeds in rice, only six were identified by Waterhouse (1992) as most likely targets for classical biological control: *Monochoria vaginalis* (Burm. f.) Presl., *Fimbristylis miliacea* (L.) Vahl, *Echinochloa crus-galli* (L.) Beauv.), *Ageratum conyzoides* L., *Sphenoclea zeylanica* Gaertn., and *Rottboellia cochinchinensis*. A stemborer, *Emmalocera* sp. was identified in Japan and Malaysia as potential biocontrol agent against *Echinochloa oryzicola* (Itoh 1991; Goto 1992).

The use of mycoherbicides (fungal pathogen inoculum) an inundative approach to biological control has been successful in certain rice systems. The most successful of these, so far, is control of the rice broadleaf weed, northern jointvetch (*Aeschynomene virginica* (L.) BSP) by the mycoherbicide Collego®. Collego® is an inoculum from an indigenous fungal pathogen *Colletotrichum gloeosporioides* (Penz.) Sacc. f. sp. *aeschynomene* and has been used since 1982 in dry-seeded rice in southern U.S. (Smith 1986). Collego® is applied with other rice herbicides like acifluorfen (Smith 1992) to broaden the weed control spectrum.

In Asia, there has yet been no successful widespread use of mycoherbicides for rice weed control. Although mycoherbicides have been used in soy beans in China. The search for potentially promising mycoherbicides is being carried out simultaneously in various laboratories in east and south-east Asia. In greenhouse and small plot field evaluations, certain rice weeds were successfully controlled by the following fungal pathogens: a leaf blight pathogen against *Sphenoclea zeylanica* (Bayot *et al.* 1992), *Epicoccosorus nematosporus* and *Nimbya scirpicola* for *Eleocharis kurogiwui* (Gohbara and Yamaguchi 1992; Tanaka *et al.* 1992), *Drechslera monoceras* against *Echinochloa* spp. (Gohbara and Yamaguchi 1992), *Alternaria* sp. for *Scirpus planiculmis* (Hong *et al.* 1991; Gohbara and Yamaguchi 1992) and *Colletotrichum* sp. and *Sphacelotheca* sp. for *Rottboellia cochinchinensis* (Watson 1992). Greenhouse and field screenings show excellent efficacy of these organisms against these weeds with good selectivity to transplant rice. However, their selectivity to direct seeded rice has yet to be determined. The greatest constraints to widespread use of mycoherbicides is low virulence, unfavourable environmental conditions, selectivity to rice in all kinds of culture and also to other crops, and development of efficient formulation and application techniques (Watson 1992). In developing application techniques, two issues should be considered: 1) feasibility of use in small-farm scale as well as large commercial scale and 2) availability of equipment or infrastructure and related materials needed in large-scale development in a particular country or locality.

Integrated Weed Management (IWM)

Even before the IWM concept was formally introduced into the science of weed control, rice farmers knowingly or unknowingly have been practising IWM. Concerted efforts towards its widespread adoption and understanding of the principles behind the practices were triggered by: 1) build-up of previously minor species (perennials) into dominant levels because of repeated use of the same methods to control existing dominant species (annuals); 2) increasing concern over pesticide effects on human health and the environment; and more recently 3) development of herbicide-resistant weeds. In a rice monocrop system, reliance on a single method can create control as well as environmental problems, thus there is a need to combine, change, or rotate several methods into an integrated approach. IWM is defined as the management system of weed populations aiming to keep infestation levels below those causing economic injury by

combining any two or more of preventive, cultural, chemical, or biological methods. The definition implies that IWM is largely a decision-making process involving 1) when to apply control measures with use of critical thresholds and 2) what combinations will provide best control at greatest profits. The long-term objectives of IWM are 1) to avoid or reduce any adverse environmental impact of control methods and 2) prevent build-up of any one weed species.

IWM practices vary among the rice cultures and localities or countries but the principles are the same. The essential factor is the number of direct and indirect control methods that can be combined economically in a given field situation. Farmers are interested in net benefits and in protecting themselves against risks. Because maximum rice yields do not necessarily mean maximum profits, the best determinants in selecting the "best-mix" combinations would be the desired degree of control, the cost of the control input, and the expected net returns from the control input. This means maximum rice yields at minimum costs of control inputs. The specific combinations of IWM methods for each country or region are in various chapters of this book.

Incomplete understanding of the principles behind IWM practices and lack of research data to guide rice farmers in the decision-making process are serious deterrents to its widespread adoption. Probably the most important questions encountered in practising IWM are: 1) when to apply control measures; 2) what control combinations are most efficient and cost-effective in a given field; 3) how IWM fits with other crop protection and rice production practices, and 4) how IWM fits into a rice grower's socio-economic conditions.

Timing of control measures is based on the use of critical thresholds of weed densities or critical periods of competition. Rice weed scientists agree that a single species threshold is not practical because several species are present in a given rice field and when one is controlled, another species takes over. Counting weed densities, whether single or mixed species, is neither feasible nor attractive to any rice grower whether in a 0.5 ha field in Asia or in a 500 ha field in the Americas. While it is recognised that critical competition occurs within the first 30 days of rice growth, the exact time to apply control measures within these first 30 days will depend on a particular weed situation in a given field. A practical criterion for determining the critical period that is easy to determine in any given rice field is needed. Weed scientists are currently working on development of techniques that involve visual assessment of weed cover in terms of leaf area to determine critical thresholds (Kropff *et al.* 1993).

Differences in weed/rice response to control measures due to variabilities in weed pressure, rice culture, environmental, and also economic factors cause difficulty in choosing the "best-mix" combinations. This is probably the reason that farmers resort to herbicides as the first and often, only option, particularly when encountering a new weed problem with still unknown control methods. Also, the economic value of indirect inputs is often not known, thus farmers frequently misjudge or do not fully appreciate their economic significance, cost-benefit ratios, and relative contribution to long- and short-term control strategies (Ampong-Nyarko and De Datta 1991). Indirect methods should be assessed and budgeted in the same way as direct methods. For example, increased frequency of ploughing or harrowing does not eliminate the need for direct control methods. A farmer then, has a choice of using fewer preplanting harrowings augmented with direct methods or to perform more harrowings with or without direct methods. Also, there are some indirect methods that cannot substitute for direct methods such as seeding rates beyond the optimum needed for adequate rice stands, or high fertiliser

rates.

Further refinement of IWM practices also means that whenever possible, weed control should be integrated with measures that further protect crops from insects, diseases, and other pests. The relationship of weeds with other pests and organisms in rice ecosystems should be considered in choosing or practising IWM methods. For example, little is known on the direct effect(s) of herbicides on insects and other pests and their natural enemies or on the indirect effects caused by controlling weeds which may be alternate hosts to these organisms. IWM should also be compatible with other crop protection and rice production practices in a comprehensive rice management system. Perhaps the greatest constraint to widespread adaption of IWM is difficulty of fitting a given technology with a given farmer's socio-economic resources and conditions.

FUTURE CONTROL OPTIONS AND RESEARCH CHALLENGES

Weed Ecology

Inadequate understanding of what constitutes weediness or what creates species dominance in rice ecosystems is probably the single biggest constraint to development of appropriate long-term management strategies. It is also a reason that rice growers and scientists often resort to quick and efficient but short term control methods which may create problems in the long run. Numerous studies have been carried out on biology and ecology of rice weeds but data are scattered and fragmented. Mapping of weed profiles in time and space, and relating dominant species shifts to changes in management practices and environmental factors in all rice-growing areas are needed. Models based on these data will help explain how management practices (i.e. herbicides) affect biotic (e.g. high seed production) and abiotic (e.g. water) factors to help create dominance in a certain species. Some examples of unexplained observations include: 1) Dominance of *Echinochloa* spp. throughout the rice growing world in spite of continuous intensive efforts to control them since the start of rice culture; 2) *Leptochloa* spp. are frequently observed, both in U.S.A. and Asia, to take over where *Echinochloa* spp. are controlled. Use of selective herbicides, which is a widely recognised reason for formerly minor but uncontrolled species to dominate, may be partially responsible. But does the herbicide factor interact with the genetic, physiological or morphological make-up of *Leptochloa* and/or management factors like water regime, to single out this species?

Molecular Biology

While breeding for resistance to insect pests or diseases has long been priority research, it is highly unlikely in the near future that rice can be bred for resistance to weeds. The next best option is to breed for weed-competitive or allelopathic cultivars or to breed for herbicide resistance in rice. Conventional or transgenic methods may be used, but with the increasing trend towards novel biotechnology approaches in pest management, transgenic methods seemingly offer great potential (Toenniessen 1991). Among monocotyledonous crops, the first successful transgenic transformation from protoplasts to whole plants occurred in rice (Hodges *et al.* 1991). The advantages and disadvantages of this new technology and these potential weed control options should be carefully studied in terms of feasibility and on short- and long-term impact on rice weed control systems.

Competitive Cultivars

Weeds are sensitive to interspecific competition, a vulnerability that can be exploited to rice's advantage by using competitive cultivars (Pamplona *et al.* 1990). The main issue to be resolved in breeding for competitive cultivars is the feasibility of combining the contrasting traits

determining high yields with those determining competitiveness. A future rice prototype with even higher yields (~15t/ha) is planned to be 10 cm shorter than the existing 100-cm, 10 t/ha yielders (Anon. 1993). Assuming plant breeders' high-yielding rice traits can be combined with weed scientists' competitive rice traits into a feasible breeding program, the next step is to explore rice species genetic diversity regarding weed competitiveness, or incorporate certain "weedy" traits into rice such as: 1) presence of chlorophyll in the first leaf (as in barnyard grass which gives it a 4-day head start over seeded rice) (Kim and Moody 1989); 2) high photosynthetic, nitrogen and water use efficiency of grass weeds (Pamplona *et al.* 1990); high potential to acclimatise to change; 4) vigorous and deeper root system with greater potential to absorb water (Pamplona *et al.* 1990) in addition to the other previously identified weed-competitive traits (Janiya and Moody 1993; Khush 1994).

Allelopathic Cultivars/Allelochemicals

There are two ways by which the principal of allelopathy can be used as potential weed control options: 1) breed for commercially acceptable cultivars with allelopathic traits; 2) develop botanical herbicides from allelochemicals. Screening studies in Japan and the U.S.A. showed that native japonica cultivars (Fujii 1992) and 4% out of 10000 rice germplasm lines (Smith 1992) possess various degrees of allelopathic activity against certain rice weeds. In small plot field trials in Arkansas, 9 out of 38 rice germplasm lines suppressed growth of duck salad (*Heteranthera limosa*) and other aquatic weeds by 80 to 90% (Lin *et al.* 1992). These lines differ in origin, grain type, plant height and maturity, which are desirable in developing commercially acceptable cultivars with allelopathic traits (Dilday 1994).

In initial efforts to develop botanical herbicides from allelochemicals, active principles of allelopathic chemicals have been isolated and identified in Asia and the U.S.A. (Kim 1992). Future research programs involving development of allelochemicals should consider availability of facilities/infrastructure needed to produce these chemicals locally, if these are done in a developing country.

Herbicide-Resistant Rice

The first foreign genes expressed in rice plants were bacterial genes conferring antibiotic or herbicide resistance. The first transgenic herbicide-resistant gene to be developed in rice is resistance to the herbicide phosphinothricin (Dekeyser *et al.* 1989) and more recently, resistance to glufosinate (Cao *et al.* 1992). Except for private chemical industries, however, breeding for herbicide resistance in rice is not considered priority research because of two major concerns: 1) increased herbicide use; 2) risk of transfer of resistance gene to weeds closely related to rice like red rice or barnyard grass by cross-pollination. Because pollen is the most likely natural source of gene exchange, risk may be minimised by use of cytoplasmically-inherited resistance (Froud-Williams 1991).

If proven commercially and environmentally feasible, use of herbicide-resistant rice would allow application at most vulnerable stages of weeds in a wide range of soil and climatic conditions and eliminate problems of selectivity which would not be possible with herbicide-susceptible rice. If the developed resistance is to a broad-spectrum herbicide it would enable a one-shot application thus reducing the number of applications in a season. If future research programs are to be developed involving herbicide resistance in rice, risk assessments should be made to ensure that problems that could possibly result from its use do not outweigh its advantages.

Participatory/Interdisciplinary Research

Basic and strategic research has produced highly efficient, scientifically sound IWM or IPM technology in rice but most of these were developed with biological efficacy as the main concern, or were developed for large scale rice farming and do not entirely apply to small-scale rice farming. Thus their adoption was low or limited largely because they do not fit a small rice farmers social, economic, or technical resources. Current research programs now recognise these adoption problems and are placing greater emphasis on farmer-oriented inter-disciplinary or participatory research involving, not only plant scientists but also economists and social scientists, environmentalists and policy makers. In contrast to previous research which started from laboratories to rice farms the starting point of participatory research is the farmer and his needs. Specific objectives of interdisciplinary farmer-oriented research are: 1) determine how weed control technology and social, economic, environment, and policy factors can compliment better adoption 2) enhance decision-making ability of farmers by making them understand or appreciate principles behind practices; 3) improve on existing technology for widespread adoption or on local practices for better efficacy.

To start with, current (and future) interdisciplinary research can look at the following indirect and direct weed control methods from a total perspective, particularly in the area of economics and policy.

Indirect methods: 1) encourage or enforce farmers' observance of weed-free seeds or weed seedling-free transplants; 2) economic or policy factors to improve irrigation infrastructure for better water control especially in tropical rain-fed and upland rice; 3) efficient and affordable small-farm equipment for better land preparation and mechanical weeding operations; 4) integration of IWM with IPM practices.

Direct methods: Use or development of safe, highly efficient herbicides with single active sites which are less resistance-prone; 2) effect of new herbicides on biodiversity of rice ecosystems; 3) improved weed control in dry soil and reduced rice injury in flooded soil; 4) safe, efficient and affordable small-farm herbicide application equipment.

CONCLUSION

The earliest weed control practices in rice were production methods of transplanting and growing rice in puddled, flooded soil. Introduction of short-statured, fertiliser-responsive, high-yielding rice cultivars and direct-seeding intensified weed pressure and competition and required more direct and more intensive weed control efforts. Current control technology consists of direct removal or control of weeds with chemical, cultural and a few biological methods. These are supplemented with indirect cultural and agroecological rice production practices which help suppress weed growth such as tillage, water and fertiliser management, cultivar use, seeding rate or plant spacing, crop rotation, and preventive practices. The kind of direct control measures and the proportion of direct and indirect measures are largely determined by economic factors, mainly cost of labour and herbicides and expected net returns. Weed control measures are highest in irrigated (transplanted or direct seeded) rice where yields and crop values are highest, than in rain-fed, upland or flood-prone rice. Improving herbicide activity in dry-seeded rice and selectivity in wet-seeded rice, better control of perennial weeds and reducing the number of cultural or chemical treatments in a season are priority concerns for direct control methods. With indirect methods, there is a need to focus attention on improving water control in rain-fed rice, use of weed-free planting materials and more thorough land preparation. Basic and strategic research on weed ecology and on participatory interdisciplinary

research is also a current priority concern in renewed efforts to a better understanding of rice weeds as well as rice farmers' needs. Feasibility and risk-benefit considerations of biological control methods and of developing competitive, allelopathic, or herbicide-resistant rice through transgenic methods as possible additional control options are important research challenges for rice weed scientists in the coming years.

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CHAPTER 4

ECONOMIC ASPECTS OF WEED MANAGEMENT IN RICE

ECONOMIC ASPECTS OF WEED MANAGEMENT IN RICE

Sushil Pandey and Prabhu L. Pingali

INTRODUCTION

Weeds are one of the most important sources of yield loss in rice. Experimental data indicate that as much as 85 per cent of yield could be lost to weeds (Smith 1983). As farmers actively manage weeds, actual yield losses are much lower. In the Philippines, thirty per cent of the yield gap between the yield attainable on farmers' fields and actual yield has been attributed to poor weed control (De Datta and Flinn 1986). World-wide loss in yield of rice due to weeds has been estimated to be around 10 per cent of total production (Moody 1991). Taking 1993 rice production to be 520 million tons, this amounts to a loss to weeds of \$14 billion.

In addition to yield loss, other losses caused by weeds are reduced quality, interference with harvesting equipment and cost of weed control. Quantitative estimates of some of these losses are very sketchy. The direct cost of weed control (cost of labour and herbicide) have ranged from 5 to 13 per cent of the total cost of production (Moody 1991). In addition to the direct cost, indirect costs of weed control include the cost of land preparation and water management carried out specifically for weed control, the effect of herbicides on useful rice field by-products, phytotoxic effects on crops and any adverse effects on human health and environment.

This paper provides: (i) an overview of the economics of weed management in Asian rice systems, ii) an assessment of the growing use of herbicides and possible environmental and health consequences, and iii) a review of regulatory and policy options for moving towards more wholistic weed management systems.

A BRIEF REVIEW OF WEED MANAGEMENT PRACTICES

Weed management practices used by rice farmers could be classified into direct and indirect methods. Direct methods refer to those that are designed mainly to control weeds. These are herbicides and mechanical or manual weeding. Indirect methods include general crop management practices which in addition to improving crop productivity also reduce weed infestations. Of the indirect methods, land preparation and water management are more critical for weed control.

Manual weeding is one of the more common methods of weed control in rice in developing countries. It can be very effective but is time consuming and laborious, especially if rice is direct seeded. It is not uncommon to find farmers using as many as 100 person days/ha for weeding under upland conditions. When rice is grown in transplanted culture, one or two manual weeding can be adequate to achieve a satisfactory level of weed control.

The demand for mechanical weed control is also governed by the opportunity cost of labour versus that of machines. Even though the relative price structure may favour mechanical weeding, technical aspects such as limited workability of existing mechanical devices in rice fields where moisture conditions can vary from dry to saturated within a short period, have restricted widespread adoption of this method.

Herbicides are becoming increasingly popular as methods of weed control in rice in developing countries. In Japan, U.S.A. and Australia, farmers rely solely on herbicides for weed control. The adoption of high yielding varieties which are responsive to weed control and the availability

of relatively cheap herbicides have led to widespread use of herbicides especially under irrigated conditions.

Land preparation, method of crop establishment, puddling, water management, date of planting, plant density, cultivar choice and fertility management impact indirectly on weed populations. Farmers manipulate these components of rice culture to achieve a certain degree of weed control. Land preparation and the choice of crop establishment method are probably the most common weed control methods. Weed populations can be substantially reduced by a number of ploughing and harrowings. Weeds are generally kept in check under transplanted conditions with good water control. In contrast, dry or wet seeded rice suffers from more severe weed problems. The technical aspects of these indirect methods of weed control have been comprehensively discussed by Moody (1991).

In a broader sense, wage rate and reliability of water supply are the major economic and environmental determinants of the choice of weed control methods (Fig. 1). In ecosystems with high reliability of water supply, puddling and water management are effective methods of weed control. In addition, herbicides are used where labour cost is high. These are the two main methods of weed control in countries like Japan, South Korea and the U.S.A. Almost all the rice area in these countries is irrigated and labour costs are high. Herbicide usage is also high in these countries (Table 1). On the other hand, manual methods are more common in countries like India, Bangladesh and Burma due to low reliability of water supply and low labour costs. Farmers who grow rice under rain-fed conditions in these countries use very little herbicide. In countries where wages are relatively higher (e.g. Philippines), herbicide usage is higher.

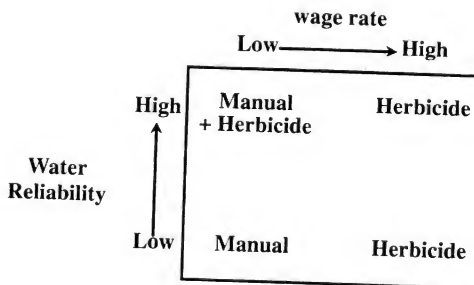


Figure 1. Hypothesized pattern of labour and herbicide use.

AN ECONOMIC MODEL OF WEED MANAGEMENT

Three basic economic questions regarding weed management are (a) whether or not weeds should be controlled, (b) what is the optimal intensity of control and (c) when is the best timing of control. Answers to these questions can be derived by using the concepts of marginal cost and marginal benefit. Hence the first step is to identify components of costs and benefits of weed control. In doing so, all costs and benefits, irrespective of whether or not they are valued in the market place should be included.

Assuming that all benefits and costs are somehow accounted for, it is then possible to apply economic principles to answer the three questions posed above. For the sake of illustration, take the case of chemical control of weeds. The level of infestation at which a chemical treatment should be applied depends on the economic threshold.

Headley (1972) defined an economic threshold as the population that produces incremental damage equal to the cost of preventing that damage. According to this concept, it will be economically profitable to control weeds if the infestation is greater than the economic threshold.

The concept can be illustrated by using a damage function which quantifies the relationship between loss in yield and weed infestation. A typical damage function is illustrated in Figure 2. Using weed density as an indicator of infestation, the damage function traces out yield losses at different densities of an uniformly distributed single species of weed. When weed density is close to zero, there is no yield loss. As weed density increases, yield losses also increase but at a diminishing rate.

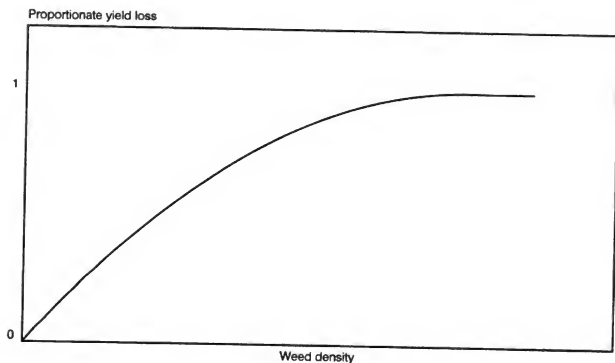


Figure 2. Relationship between weed density and yield loss.

Table 1. Herbicide use in rice.

Country	Value of herbicide use ^a (\$m)	Herbicide use/ha ^b (\$/ha)	Percent rice area irrigated ^c	Wage rate ^c (\$/day)
India	23	0.55	44	1.03
China	80	0.41	94	1.03
Bangladesh	5	0.47	19	1.42
Indonesia	6	0.60	81	1.14
Thailand	18	1.8	27	1.83
Philippines	11	3.14	59	2.1
Japan	659	314	100	45
South Korea	110	92	100	22
USA	100	91	100	-
Other Countries	158			
Total	1170			

Source: ^a Ciba-Geigy, Personal Communication, 1994

^b Rice area obtained from IRRI (1991)

^c IRRI (1991)

In Figure 3, losses are expressed in money terms by multiplying the physical yield loss from Figure 1 by the price of output. A treatment that costs \$ c /ha is worthwhile only if the value of yield loss prevented is greater than \$ c /ha. There is a critical weed density (W^*) the economic threshold, at which this condition is satisfied. In the diagram, weed control is desirable only if weed density is above W^* .

The concept of economic threshold, although simple and intuitively appealing, has several limitations. The threshold, although presented in physical terms (i.e., number of weeds/m²), depends on the cost of weed control as well as the price of output. A new economic threshold needs to be calculated every time these prices change. This makes the implementation of the concept somewhat cumbersome. A more serious limitation is that the intensity of weed control input is not allowed to be varied. In addition to decisions on whether or not to control weeds, farmers also have to decide on the intensity of weed control. Farmers may wish to alter the intensity of weed control by applying more or less weeding labour or herbicides. When weed control inputs are divisible, the threshold concept loses much of its usefulness.

A more defensible economic approach to weed control is presented in Figure 4 in which marginal revenue (MR_w) and marginal costs (MC_w) of weed control are presented as a function of weeds removed per unit area. For a given initial weed density, the marginal cost is assumed to increase

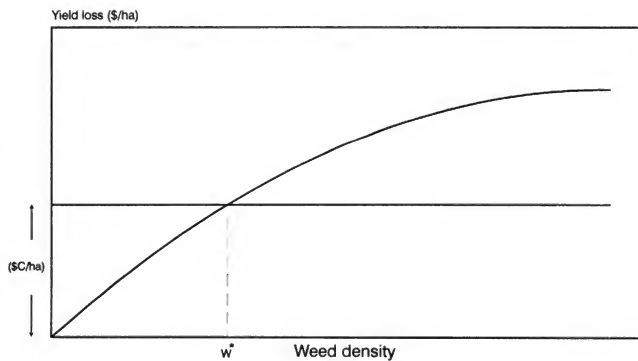


Figure 3. Economic threshold for weed control.

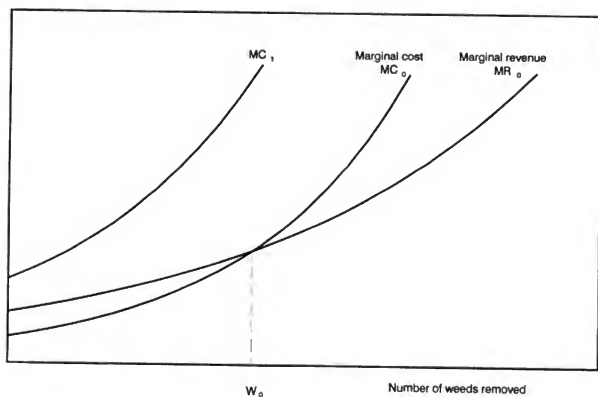


Figure 4. Economically-optimal level of weed control for a given level of infestation.

as more weeds are removed (either by chemical or by manual methods). For the assumed shape of the yield loss function, the marginal benefit of weed control increases as more and more weeds are removed. Profits are maximised when W_0 weeds are removed. If the additional profit realised at this level of weed control is greater than the fixed cost (such as the cost of labour contract, movement of spraying tools to the farm etc.) associated with a decision to control weeds, it would be rational for a profit maximising farmer to choose W_0 level of weed control. In the contrary situation, it would be optimal not to control weeds. Similarly, if the marginal cost curve is above the marginal benefit curve throughout its range (as with MC_1 in Figure 4), weed control technology is too expensive relative to benefits expected and no weed control will be practised.

Thus answers to both the first and second questions can be provided by applying the economic rules for optimisation. The optimal timing for weed control can similarly be derived, although in most situations, a biologically "critical" window outside which weed control may not be effective could be identified.

In the above framework, incremental costs and benefits of weed control were assumed to be realised in the current production period. By altering the size of the seed bank, current weed control decisions also affect future infestations, and hence, future benefits. Even though infestation in the current production period is below the economic threshold, some degree of weed control may be justifiable if future benefits are also taken into account. A multi-period framework which takes into account benefits and costs not only in the current production period but also future streams of benefits and costs are required (Pandey and Medd 1991). Such an approach is essential for a long-term management of weed population rather than a short term "cure" of the weed problem. Empirical studies on other crops have indicated that, compared to the short-term approach, a long-term approach to weed management can reduce weed population to a lower level and generate greater economic benefits (Cousens *et al.* 1986; Pandey and Medd 1991). The approach could also be applied to rice weeds where seed bank is the main source of seed carryover (Kim and Mercado 1987). In addition, the multi-period framework provides a basis for incorporating such long-term effects as herbicide resistance and the effect of herbicide use on human health and environment.

Risk considerations can be important in determining farmers' choice of methods and intensity of weed control in rice fields. Unlike other inputs such as water and fertilisers, weed control inputs are 'protective' in the sense that they help reduce damage. Such inputs are generally considered to be 'risk-reducing'. Depending on the source of uncertainty herbicides could be risk reducing or risk increasing (Pandey and Medd 1991; Horowitz and Lichtenberg 1994). To the extent that they actually reduce risk, risk averse farmers would tend to apply more weed control inputs than risk neutral farmers.

Risk aversion could also be an important factor in determining the level of weed control inputs applied by rice farmers. Weed management practices which function effectively only under very precise management and environmental conditions may be perceived to be too risky by farmers. In the Philippines, farmers use low levels of weed control input even though the marginal benefit cost ratio associated with high intensity weed control practices is large (Table 2). In addition to credit constraints, such a behaviour could be due to risk aversion.

Table 2. Economic comparison of high levels of weed control input with farmers' current practices in irrigated rice in three Philippine provinces, 1984 dry season.

Location	No. of sites	Weed control cost (US\$/ha)			Profit (US\$/ha)		Benefit:Cost ratio
		F	R	(R-F)	F	R	
Bulacan	2	2	9	7	54	87	5
Camarines Sur	15	8	9	1	120	143	26
Nueva Ecija	11	11	9	-2	121	172	>25

*F = Farmers'; R = Researchers'

Risk considerations are also important in the choice of pre-emergence versus post-emergence herbicides. Pre-emergence herbicides have to be applied before weeds emerge. The application hence is prophylactic. On the other hand, post-emergence herbicide use is more flexible as it can be tuned to the level of infestation. Farmers may, however, opt for prophylactic applications if they believe that post-emergence control is too risky.

EVOLVING TREND TOWARDS INCREASED HERBICIDE USE

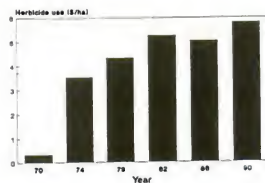
The use of herbicides to control rice weeds has increased over time (Table 3). The Philippines, Thailand and India have more than doubled their herbicide imports in the 80s. Farm-level data for the Philippines and Vietnam indicate that there has been an upward trend on expenditure on herbicides (Figure 5).

Table 3. Change in the value of herbicide imports in selected Asian countries.

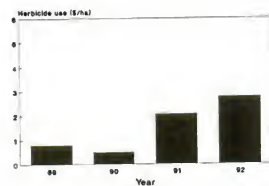
Country	Period	Percentage change in the value of herbicide imports
Philippines	1984-88	165
Thailand	1980-90	217
India	1987-90	272
China	1987-90	23
Indonesia	1984-88	94

Source: FAO (1988)

The total value of herbicide sales in rice-producing countries has been estimated to be more than \$1.2 billion in 1993 (Table 1). Over 50 per cent of this total is used in Japan. The share of developing countries is about 20 per cent (Figure 6). Several factors have contributed to



Herbicide use (\$/ha) Central Luzon, Philippines.



Herbicide use (\$/ha) Mekong Delta, Vietnam.

Figure 5. Farm level herbicide use in the Philippines and Vietnam.

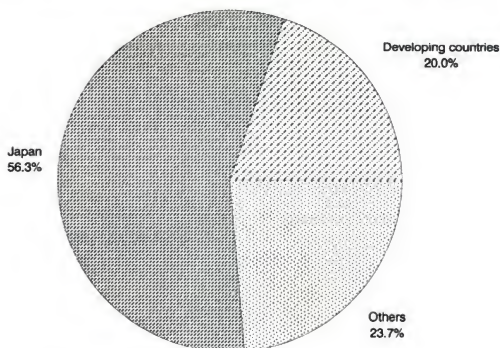


Figure 6. Global herbicide use in rice 1993.

increased popularity of herbicides for weed control. These can be classified into technological and economic factors.

The traditional varieties of rice, although low yielding, were naturally competitive with weeds due to their early vegetative growth, tall stature and drooping leaves. Modern high yielding varieties are relatively less competitive. Thus compared with traditional varieties, modern varieties tend to be more heavily infested by weeds. Due to the higher yield potential of modern varieties, yield gains obtained from a given intensity of weed control are also higher.

Widespread adoption of high yielding varieties thus created economic incentives for farmers to reduce weed infestations. Simultaneously, cheap herbicides became available while wage rates increased. In the Philippines, the ratio between price of herbicide and wage rate declined steadily over time, making herbicide use economically more attractive (Fig. 7). In Iloilo province, Philippines, the cost of weed control by herbicide in wet seeded rice is less than one-fifth of the cost of a single hand weeding (Moody 1994). Similarly, in West Java and Mekong Delta, the cost of hand weeding is 3 to 5 times the cost of herbicides. Economic analysis of weed control practices in the Philippines indicates that the marginal benefit-cost ratio associated with herbicide usage is as high as 16 (Table 4).

The cost-price squeeze ensuing from a long term decline in prices received for rice (Fig. 8) and increasing wage rates (Fig. 9) forced farmers to adopt cost saving methods. A major response to this has been a shift from transplanting to direct seeding. Direct seeding consists of sowing rice seeds directly in the soil mostly by broadcasting. Thus direct seeding methods save on labour cost substantially. Most of the irrigated rice in Malaysia is wet seeded. Wet and dry seeding methods are becoming increasingly popular in other rice producing countries also. Direct seeding, especially dry seeding, is also encouraged by the possibility of intensification of cropping systems. Even though weed control costs are higher for direct-seeded rice, savings in labour cost have been more than the additional cost of herbicide (Table 5).

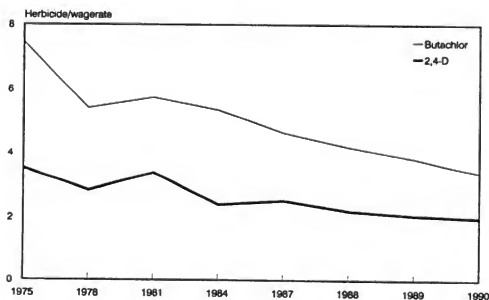


Figure 7. Real price of herbicides (Philippines).

Table 4. Economics of weed control in irrigated transplanted rice^a, Philippines, 1990

Control method	Grain yield (t/ha)	Total variable cost ^c (US\$/ha)	Total return (US\$/ha)	Return above variable cost (US\$/ha)	Marginal benefit-cost ratio ^d
No weeding	1.5	0	263	263	
2 hand weedings ^b	3.7	90	648	558	3.3
Thiobencarb/2,4-D (1.0 + 0.5 kg/ha)	3.3	19	578	559	16

^a Data on rice prices and yields were obtained from IRRI (1991). Data on physical inputs and yields were obtained from Ampong-Nyarko and De Datta, using analysis from previous IRRI studies.

^b Assumptions: Labour = US\$2.09/day; 2 handweedings = 43 day/ha; Cost of herbicides = US\$ 19.

^c Total variable costs reflects costs for weed control only.

^d Marginal benefit-cost ratio = change in returns above variable cost over change in total variable cost.

Source: Naylor (1994)

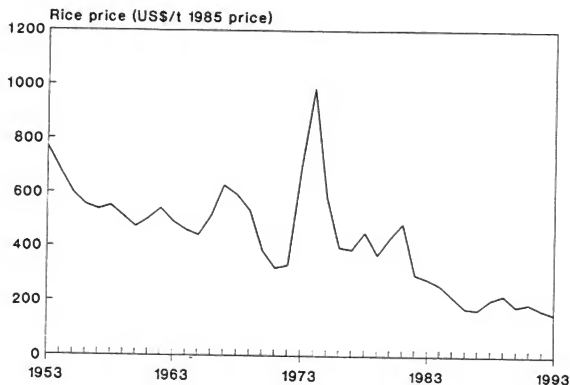


Figure 8. Trends in world rice price, 1953-93.

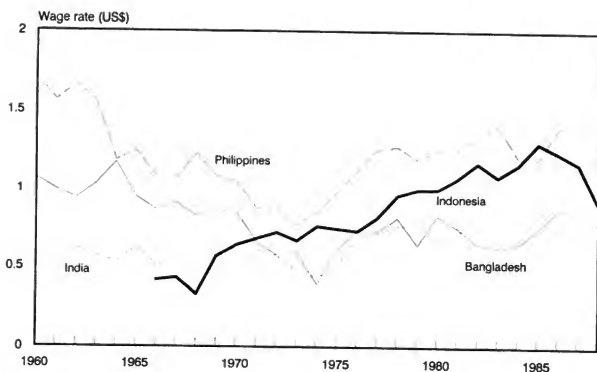


Figure 9. Real wage rate (1975 price).

Table 5. Herbicide and labour costs associated with wet seeding and transplanting methods of rice establishment.

Country	Herbicide cost (\$/ha)			Pre-harvest labour cost (\$/ha)		
	Trans-planted	Wet-seeded	Add-itional	Trans-planted	Wet-seeded	Add-itional
Philippines ^a	7	9	2	36	8	-28
Malaysia ^b	6	20	14	205	114	-91

^aErguiza *et al.* 1990

^bHo 1994

Weed problems are, however, more serious in direct seeded rice than in transplanted rice. As weeds and rice emerge simultaneously in direct seeded fields, the competitive effect of weeds on rice is much greater. The success of direct seeding method depends critically on weed control. Empirical studies in the Philippines and Vietnam indicate that farmers who use wet seeding relied more heavily on herbicides than farmers who transplanted and that there has been a shift away from manual method towards herbicides use (Tables 6 and 7). Similarly, in Peninsular Malaysia, 95 per cent of farmers who direct seeded applied herbicides, with an average herbicide cost of \$ 30/ha. On the other hand, only 46 per cent of the farmers who transplanted used herbicides, with average expenditure on herbicides being \$ 4/ha (Moody 1994).

Table 6. Weed control practices by crop establishment methods.

Country	% of Farmers	
	Transplanted	Wet-seeded
Philippines		
-Manual only	8	0
-Herbicides only	52	71
-Herbicides + manual	34	27
-None	6	2

Table 7. Changes in weed control practices over time in Vietnam.

Method of crop establishment		% of farmers in various years			
		1989	1990	1991	1992
Dry Seeded	Herbicide + Manual	48	47	67	71
	Herbicide only	12	16	16	16
	Manual only	38	36	15	12
	None	2	1	2	1
Transplanted	Herbicide + manual	23	33	59	71
	Herbicide only	2	0	10	18
	Manual only	71	67	27	12
	None	4	0	5	0

Herbicide use is increasing even in areas which are transplanted. Increasing unreliability of water due to a host of factors including deterioration in irrigation infrastructures (Rosegrant and Pingali 1991) has made weed control via water management somewhat uncertain.

In addition to general increases in wage rates the seasonality of demand for labour often results in labour scarcity during the optimal time for weed control. The peak of labour demand for weeding is likely to be accentuated in more intensive production systems. Thus, demand for chemical methods can be expected to increase as rice production is intensified.

Although economic and technological factors are likely to lead to increased substitution of labour by herbicides, such a substitution may result in short term adverse social consequences. Due to the need to complete weeding within a short time window, farmers rely on hired labour for weeding (Table 8). As small and marginal farmers are the main source of hired labour, their income and employment will be adversely affected unless they can find an alternative use of their time. Increase in cropping intensity made possible by improved technology has in the past been able to absorb most of the displaced labour (David and Otsuka 1994). The extent to which substitution of labour by capital in agriculture will occur without imposing welfare costs on certain groups depends mainly on government policies on exchange rates, pricing of inputs and outputs and macro-economic policies. To the extent that herbicides are made cheaper relative

to labour due to distortionary price policies, substitution of herbicides for labour is socially undesirable. In addition, negative environmental and health effects of herbicide use entail additional social costs.

Table 8. Labour use by operation by method of crop establishment, for three locations in the Philippines; Wet season 1981 and 1982.

	Bulacan-N. Ecija		Iloilo		Camarines Sur	
	WSR	TPR	WSR	TPR	WSR	TPR
Labor use (man days/ha)						
Land preparation	6 (57)	8 (48)	8 (38)	8 (38)	7 (71)	14 (43)
Seeding/transplanting	1 (12)	20 (100)	1 (0)	13 (92)	1 (0)	18 (100)
Handweeding*	3 (23)	3 (29)	7 (29)	19 (74)	5 (40)	1 (54)
Other pre-harvest	8 (32)	13 (38)	1 (0)	2 (50)	1 (0)	1 (0)
Total pre-harvest	18	44	17	42	14	44

TPR = transplanted rice; WSR = wet-seeded rice

*Includes replanting and handweeding.

Figures in parentheses indicate % of hired labor.

Source: Cordova *et al.* (1984).

INTER-FARM DIFFERENCES IN WEED CONTROL METHODS

Despite an increasing trend in the use of herbicides in rice production in Asia, manual weeding is still the most common method of weed control, especially in rain-fed areas. As mentioned earlier, the choice of a particular method depends on its cost relative to the gains expected. In rain-fed areas, where yield of rice under weed-free conditions is lower than that under irrigated conditions, the intensity of weed control input is also likely to be lower. Thus part of the observed inter-farm differences could be due to access to irrigation.

Whereas the optimal intensity of weed control depends on yield response to weed removal, the relative opportunity costs of labour and chemicals are important in determining the preferred method. Even within an homogeneous agroecological environment, there are inter-farmer variations in the choice of weed control methods. Such variations may depend on farm size, family size, tenurial status and access to credit. Small farmers for whom the opportunity cost of family labour is likely to be low rely predominantly on manual weeding in contrast to large commercial producers. Substitution of family labour by herbicides entails additional cash cost. Herbicides will be less attractive to farmers who have limited access to credit. To the extent that tenants are relatively poor and have limited access to credit, they are unlikely to use cash intensive inputs such as herbicides. But the intensity of weed management by tenants depends largely on cost and output sharing arrangements. Empirical evidence across countries does not

show any consistent differences in weed management practices between tenants and landowners (Denning *et al.* 1983).

Cash constraints can also force farmers to substitute rice seeds for herbicides, especially in direct-seeded rice. In the Philippines, farmers use a high seeding rate (150 kg/ha) to decrease the competitive effect of weeds. Experimental work indicates that a high seeding rate does help control weeds (Moody 1991). However, with high seeding rate, fertiliser requirements can also increase negating some of the weed control benefits.

The degree of weed control applied depends also on systems level interactions. For example, farmers in rain-fed areas of the Philippines and Bangladesh use weeds as fodder. Weeds are removed from rice fields only when they are sufficiently tall to be cut. By this time, weeds would have exerted most of the competitive effects on rice. Apparently, farmers consider the value of fodder to be greater than the loss of yield due to weeds. Weed control decisions could be affected similarly if farmers obtain other useful products from rice fields (for example, fish and vegetables).

Although rotation of rice with dry-land crops is believed to help reduce infestations of difficult-to-control weeds (Moody and Drost 1983), it is not clear the extent to which farmers use crop rotation mainly for weed control. Hydrological conditions may restrict the possibility of growing a dry-land crop. Furthermore, conversion from wetland culture to dry-land culture may require additional cost in land and water management.

Rotation of rice establishment methods for weed control is practised by farmers in Iloilo province, Philippines. After wet seeding for several years, farmers with access to irrigation switch to transplanting to help control weed infestations built up during the wet seeding phase. Both the weed density and weed weight were found to be substantially reduced in a cropping pattern of dry seeded rice followed by transplanted rice (Moody and Drost 1983).

ENVIRONMENTAL AND HEALTH CONSEQUENCES OF HERBICIDE USE

Careful measurement and documentation of the environmental and human health consequences of pesticide use are rare for developing country agriculture. In the case of rice, the International Rice Research Institute recently completed a detailed farm level assessment of the long term impacts of pesticides in the Philippines (Pingali and Roger 1995). In the case of rice, Philippine evidence indicates that indiscriminate pesticide use, both insecticides and herbicides, can have serious environmental and health consequences. The environmental effects are primarily in terms of ground water pollution, reduction of vertebrate populations in surface water systems and the disruption of the long term species equilibrium in the paddy ecosystem (Pingali and Roger 1995). At current low levels of pesticide use and given that the chemicals used degrade rapidly in the humid tropical climate, the environmental effects are small but one should not discount the potential for larger future effects. Concern for potential future adverse impacts is particularly strong when the rapid growth in herbicide use in Asian rice production is considered.

The health effects of pesticide use in the Philippines, even at current levels, are quite substantial (Pingali *et al.* 1994; Rola and Pingali 1993; Antle and Pingali 1994). Eye, skin, pulmonary and neurologic problems are significantly associated with long term pesticide exposure. The majority of the pesticides which might be linked to these impairments, the highly hazardous category I and II chemicals, while commonly available in the Philippines are banned or severely restricted

in the developed world. Herbicides have been particularly implicated in the high incidence of skin diseases, polyneuropathy, and gastro-intestinal problems (Pingali *et al.* 1994).

Rola and Pingali (1993) found that the net benefits of insecticide use are negative when health effects are explicitly accounted for. Antle and Pingali (1994) found that insecticide related health impairments cut farm household productivity. When insecticide use is reduced, the value of the positive health benefit of reduced exposure is invariably greater than the value of the crop lost to pests. In the case of herbicides, the health - productivity trade-off is less clear. In the case of a switch from transplanting and manual weeding to direct seeding with herbicide use, the positive productivity benefits are substantially greater than the value of the adverse health effects (Pingali and Roger 1995). On the other hand, the productivity benefits of a switch to herbicides in transplanting systems are smaller and may not outweigh the health costs associated with herbicide exposure. Table 9 provides a comparison of yields and net benefits for alternative weed management strategies with and without considering health costs. For details on the methodology used for the above ranking see Pingali and Roger (1995).

Table 9. Mean net benefits of weed control strategies incorporating health cost (\$) for Nueva Ecija rice farmers, Philippines.

Weed control strategy	Yield (kg/ha)	Mean net benefits		
		Estimated health costs (\$)	Without health costs (\$)	With health costs (\$)
Transplanting + Handweeding	5043	0	666	666
Transplanting + Handweeding + Herbicide	4927	5	668	663
Direct seeding + Herbicide	5131	5	818	813

POLICY AGENDA FOR WEED MANAGEMENT AND HERBICIDE USE

An optimal pesticide policy revolves around possible ways of ensuring its effective use, that is, of promoting agricultural productivity while minimising the health and environmental effects. The following are the elements of a preferred scenario for pesticide use, both insecticides and herbicides.

Judicious and Safe Use of Chemicals

The movement away from prophylactic pesticide applications to a wholistic management of the plant, pest, predator system will reduce pesticide requirements, even for intensively cultivated systems. However, integrated controls are knowledge intensive and location specific, they require substantial allocations of technical and administrative resources in farmer training and extension programs. Farmer training ought to also include safety procedures in handling, storage and disposal of chemicals.

Evidence from the developed world and more recently from the developing world indicates that there is no productivity loss in substituting category I and II chemicals with category III and IV chemicals. For example, the switch from category II herbicide, 2, 4-D, to a category IV herbicide, butachlor, does not lead to a loss in productivity. In fact, if the health gain associated with reduced exposure to the highly hazardous chemicals is accounted for, then there could actually be a net productivity gain in the switch to category III and IV chemicals.

In registering or re-registering pesticides for use in a country, the regulatory agency ought to have an improved understanding of the productivity benefits as well as the risks of pesticide use. Risk-benefit assessment is the appropriate analytical tool for making such decisions. While country specific measurements of impacts would give the most accurate technical coefficients for risk assessment, the value of similar information collected elsewhere should not be discounted, at least in a prior probability sense. An improved understanding of the trade-offs would allow the regulatory agency to be more discriminatory in its choice of chemicals to import and/or register. Farmers with improved knowledge of consequences of pesticide use, could be equally discriminating in their choice of pest control strategies.

Tariffs/Taxes

Price and tariff interventions could be used to encourage the shift to safer chemicals and to non-chemical pest control practices. Very high tariffs especially on highly hazardous pesticides could discourage importers from promoting these chemicals. Very high rates of taxes of category I and II, versus the category III and IV could encourage farmers to shift to safer chemicals.

Antle and Pingali (1994) provide simulation results for Philippine rice production to show that, while a uniform tax on insecticides and herbicides has negative effects on productivity, a tax on insecticides alone has a significant positive effect on productivity. Insecticides used in the Philippines are the highly hazardous category I and II chemicals. A reduction in the use of these chemicals has significant positive farmer health benefits, which leads to an increase in productivity. The loss in productivity resulting from increased pest related yield losses is more than offset by the gain in productivity from improved health. The social benefits of restricting insecticide use are substantially higher than the social costs. The same argument does not hold for herbicides, because: i) herbicides used are, generally, the less toxic category III and IV chemicals, therefore the health benefits are smaller; and ii) the yield response to herbicide use is substantially higher than the response to insecticide use.

ASPECTS OF INTEGRATED WEED MANAGEMENT

Given the trend towards increased herbicide use and the likely environmental and health consequences of such a trend, integrated weed management involving a combination of several methods is desirable. In fact, most rice farmers adopt some form of integrated weed management practice (De Datta and Baltazar 1994).

Long term management of weed populations without excessive reliance on only one method is the main purpose of integrated weed management. Reducing the build-up of the weed seed bank is a major aspect of such a long term strategy. A good understanding of the population dynamics of weeds helps identify intervention points which may be more effective in regulating weed populations than the more conventional approach of killing weeds.

The seed bank of a self-contained population of weeds can be manipulated by altering recruitment, seedling mortality, seed viability and fecundity. Herbicides and weeding reduce population by increasing seedling mortality. Ploughing, harrowing and other pre-planting operations help deplete seed bank by altering recruitment. Fecundity is reduced by removing late-emerging weeds before their seeds are shed. By putting seeds at varying depths, deep ploughing can alter seed viability.

In the case of rice, two major methods of weed management have been the manipulation of recruitment and seedling mortality. The population dynamics of rice weeds have not been widely studied to be definite about the importance of these two interventions relative to regulation of fecundity. However, in the case of wild oats, economic returns to the regulation of fecundity have been estimated to be high (Pandey *et al.* 1993). When this tactic was combined with post-emergence herbicide treatments, the seed bank of wild oats declined rapidly and a long-term control of the weed was made possible (Pandey and Medd 1990).

A tactic that is relevant to rice farmers is to use clean certified seeds. Weed seed contamination is one of the major factors for dispersal of weeds of rice (Moody 1993). In the Philippines, approximately 24,000 weed seeds were found in a kilogram of rice (Rao and Moody 1990). When farmers keep their own seeds, contaminated seeds can add substantially to the seed bank, despite their attempts to clean the seeds (Moody *et al.* 1993).

Using more competitive varieties of rice is another tactic for reducing the effect of weed competition. However, in the case of rice, there appears to be a trade-off between competitive ability and yield (Moody 1991). Research on varietal improvement for weed management in rice is at its very early stage (Khush 1994).

CONCLUSIONS

The importance of weeds in rice production is likely to grow rather than diminish with continuing population induced increases in land use intensity. Rice weed management problems are compounded by growing water scarcity and by the rapid shift from transplanting to direct seeding. Herbicide use is expected to keep growing as farmers shift from hand-weeding in response to rising wage rates.

The challenge for weed management research is to develop control strategies that sustain and/or enhance farm profits while safeguarding the environment and human health. Strategies that are sustainable over the long term are more likely to be wholistic in approach and well integrated with other crop management practices. Emphasis ought to shift from quick-fix solutions to problem prevention.

Farmer incentives for adopting a wholistic weed management approach depend upon the relative prices of rice, labour and herbicides. Where herbicide prices do not reflect the true social costs, indiscriminate use will persist. Regulatory policy could help change the relative price structure in order to reflect social costs associated with injudicious herbicide use. A three-pronged regulatory approach aimed at producers would be: i) cancellation of the highly hazardous and/or persistent chemicals; ii) selective taxation to make the liberal use of all chemicals expensive; and iii) farmer training in the judicious and discriminate use of chemicals.

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CHAPTER 5

WEED MANAGEMENT IN TRANSPLANTED RICE

WEED MANAGEMENT IN TRANSPLANTED RICE

Ze-Pu Zhang

INTRODUCTION

More than three hundred species and one hundred genera belonging to more than sixty plant families have been reported as weeds in transplanted rice fields. The weed flora varies depending upon soil type, climatic conditions, cropping systems, cultural practices, irrigation and weed control methods. The dominant weed flora in any one paddy field is usually about ten species, of which the dominant ones rarely are more than 3 to 4. Weed control in transplanted rice fields is basically directed toward controlling the following species: *Echinochloa crus-galli* (L.) P. Beauv., *Scirpus planiculmis* Fr. Schmidt, *Sagittaria pygmaea* Miq., *Potamogeton distinctus* A. Bennett, *Paspalum distichum* L., *Cyperus serotinus* Rottb., *Leptochloa chinensis* (Roth) Nees, *Monochoria vaginalis* (Burm.f.) Kunth, *Scirpus juncoides* Roxb., *Cyperus difformis* L., *Eclipta prostrata* (L.) L., *Polygonum amphibium* L. and *Alternanthera philoxeroides* (Mart.) Griseb.

Yield losses caused by weeds in transplanted rice fields depend upon the time of weed infestation, soil fertility, rice cultivar and planting methods. In transplanted rice fields, about 60% of the weeds emerge in the period between one week and one month after transplanting. These emerging weeds are the major population competing with rice in maximum tillering stage and reducing the number of panicles causing the yield reduction. About 15-20% of the weed population emerges in the period between one month and two months after transplanting and 20-25% of weeds emerge later and are not important in yield reduction. Increasing the rate of fertiliser application and the use of the younger seedlings associated with adoption of semi-dwarf, early maturing and erect rice cultivars or the use of smaller rice seedlings and a longer interval between puddling and transplanting to allow the soil to become firm in machine-transplanting increase the weed problem. Keeping the paddy field weed free until the transplanted rice crop reaches the jointing stage and controlling weeds at the appropriate time ensures that high rice yields can be obtained. Elimination of weeds from paddy fields through proper manipulation of land preparation, date of planting, crop spacing, water management and chemical weed control will also achieve high rice yields. However if weeding is not carried out at the appropriate time, crop yield will be reduced to a low level.

Worldwide losses in transplanted rice from weeds within the past decade are estimated to be about 300 kg/ha annually. In addition to yield losses, costs of 3-5% due to herbicides, manual weeding and cultural practices have been estimated.

PRINCIPLES OF INTEGRATED WEED MANAGEMENT IN TRANSPLANTED RICE

The choice of the weed management methods depends upon climatic conditions, soil type, control technology available, type of rice culture, the farmer's economic situation and the cost of weed control in comparison with the estimated value of the resulting yield increase. Elimination of weeds from paddy fields through properly manipulating soil moisture by land preparation, timely cultivation, plant spacing and maintaining favourable ecological conditions, integrated with chemical weed control is a most effective measure and is being warmly accepted by farming people. Herbicides are highly effective, low-cost and safe to rice. However much time and effort in studies on herbicide effects on weed flora weed resistance to herbicides in different ecological rice regions are required. Intensive cropping systems can increase the competitive ability of crops, thereby reducing weed pressure. Weed control is much more intensive where the farming people can achieve high rice yields. After harvesting, cutting and

burning of rice stubble and residual matter to reduce weed seeds on the soil surface and in autumn or winter time ploughing the crop fields to a depth of 20-30 cm are effective measures to reduce infestations of annual and perennial weeds in paddy fields. Most perennial weeds of rice multiplying vegetatively by means of overwintering buds, stolons, bulbs or rhizomes are more difficult to eliminate with chemical control. Deep autumn ploughing can expose the vegetative organs of the perennial weeds such as *Sagittaria pygmaea*, *Cyperus serotinus* and *Eleocharis kurogiwui* Ohwi to winter cold resulting in the drying and freezing of these organs. As an example, one autumn ploughing to a depth of 20 cm reduced *Potamogeton distinctus* about 60% compared with that check fields. Even if the fields were ploughed to a depth of 15-18 cm in comparison with a shallow rotary tillage to a depth of 10 to 15 cm, the density of weeds was reduced significantly.

In the growing season, a first tillage carried out about one month before sowing can remove perennial weeds; a second tillage done at two weeks before sowing encourages germination of weeds after rotovation, and a last tillage at one to three days before sowing followed by levelling paddy fields can eliminate weed emergence. Land levelling is very important for keeping uniform depth of water enabling rapid drainage and reflooding for satisfactory rice stands, as well as killing weed seedlings by submerging.

Double cropping of rice with wheat, oil-seed rape, barley, broadbeans or other winter cropping crops in some temperate regions is an effective cropping system for reducing perennial weeds.

Rotating rice with a dryland crop such as maize, cotton, sweet potatoes, sesame, or soybeans can reduce infestations of water tolerant weeds in rice. A one-year rotation of paddy fields to dryland condition reduced *Sagittaria pygmaea*, *Leptochloa chinensis* and *Echinochloa* spp. Weeds in rice increase as the length of time after reconversion to wetland field increases.

Shallow cultivation has the advantage of not exposing weed seeds from deeper soil layers to the surface where conditions are favourable to weed germination. Shallow cultivation before sowing can destroy seedlings and sprouts of annual weeds.

The use of tall old seedlings of rice in transplanted rice field raises the competitiveness of rice to weeds, minimising *Scirpus planiculmis* infestations and; also, close spacing in rice culture enhances the competitive advantage of the crop plants to annual grass weeds.

Together with rural economic development, transplanted rice production areas aimed at increasing rice yields and reducing workdays in mechanical and hand weeding, chemical weed control is expanding. Time of application and types of sequential treatment adopted by farmers differ, depending upon climatic conditions, cropping system, and weed flora. The herbicides used in transplanted rice include pre-emergence soil treatment, early post-emergence soil treatment and foliage treatment. The use of pre- or post-emergence herbicides such as butachlor, oxadiazon and other relatively less selective herbicides to control weeds in rice seedbeds sometimes causes severe phytotoxicity to rice due to the climatic conditions and inappropriate application methods. Post-emergence herbicides or foliar applied herbicides used in both seedbeds and transplanted rice fields should have more selectivity, otherwise the rice seedlings may easily be damaged. Continuous use of the same herbicides on rice for a number of years causes weed flora shift problems and development of resistant weed populations. In some areas, weed populations have been shifting from grasses to broadleaf weeds or from broadleaf to grass weeds. For example, the long-term use of thiobencarb, molinate or nitrofen in transplanted rice

resulted in the elimination of the dominant *Echinochloa* spp. population and the broadleaf weeds or sedges became dominant. Use of alternative herbicides and integrated weed management can overcome these problems.

WEED MANAGEMENT IN RICE SEEDBEDS

The major weeds in seedbeds of rice are *Echinochloa* spp. After transplanting, about 5% of weed population grows with rice in the planting hills, each weed plant can develop 5 to 10 tillers with an extensive root system, causing crop yield reduction up to about 30%. So, it is very important to eliminate these weeds at the rice seedling stage before transplanting by keeping the planting hill weed free as well as possible in paddy fields.

The most important preventive weed control method for rice seedbed can be practised through seed selection using high quality, uncontaminated rice seeds, proper land preparation and water management, cleaning out weeds on levees and field margins, screening out weed seeds from irrigation water and cleaning implements to avoid spreading weed seeds or propagules from field to field.

Water-seeded rice can give the best stands in a continuously flooded seedbed, but water seeding of rice does not produce seedlings. Dry-seeded rice germinates and the seedlings grow slowly but stronger than those growing in a continuously flooded seedbed and they recover more quickly after transplanting. However, dry-seeded rice seedbeds have more weeds and control is more critical than in water-seeded rice. Weed seedlings growing together with rice in the broadcast seedbed are more difficult to control using mechanical or hand weeding and farmers tend to adopt chemical weed control methods. High seeding rates in rice seedbed compete with weeds, in some regions, seeding rates at more than 1000 kg/ha are popular and seed rates as high as 2200 kg/ha have been used. An increase of seeding rate from 500 kg/ha to 1500 kg/ha resulted a significant reduction in weed density, broadleaf weeds are most affected and sedges least affected by increasing seeding rates.

Water management in rice seedbeds is a major tactic for weed control. In water-seeded rice seedbeds, irrigation is maintained to keep water 10 to 20 cm deep for a few days before sowing and 10 cm immediately after sowing. Water is drained off as rice germination begins. After most rice has emerged, seedbeds are flooded again to a depth of 10-15 cm until weed seedlings die. Water depth can be reduced to the level of seedling leaves. If the rice seedbed soil does not retain moisture to saturation, aeration in soil will encourage the weed germination and growth.

In the rice seedbed, weeds begin to emerge in 4-5 days after sowing, and most weeds emerge in 7-8 days, then the number of emerging weeds decreases. The dominant weeds are *Echinochloa* spp., and a practical way to control them is with chemicals combined with cultural practices.

A substitutive- preventive method is called the stale seedbed technique. This technique involves the removal of successive weed plants before broadcasting rice seed. Weeds germinating after land preparation following rain or irrigation are destroyed manually, mechanically or chemically. This technique has the advantage of not bringing more weed seeds to the soil surface where conditions are favourable to weed germination, but it gives no advantage if planting is delayed too long.

Nearly 100% of annual weed seeds at less than 1 cm depth emerge about one week after seeding; at 1-3 cm depth they germinate after about three weeks; and most weed seeds below 5 cm depth

do not emerge. Herbicides should be applied, or cultivation should be done, when most of the weed seeds in surface soil have germinated and some weeds are from the two- to five-leaf stage.

For pre-emergence application of herbicides butachlor e.c. 60% at the rate of 900-1800 g ai/ha or thiobencarb 50% e.c. at 2000-3000 g ai/ha are usually used in Asian countries. However thiobencarb is safer than butachlor to rice. Post-emergence application can be carried out after rice emergence from coleoptile to the one-leaf stage while weeds are at the 1-2 leaf stage. After draining water from the seedbeds, propanil 20% e.c. at 1800-2400 g ai/ha can be applied by spray for *Echinochloa* spp. control under high air temperatures and intense sunlight. A tank mixture of propanil 20% e.c. at 1000-1500 g ai/ha and molinate 90.8% e.c. at 2000 g ai/ha applied for controlling *Echinochloa* spp. at 2-3 leaf stage may achieve effective results. Some herbicides such as butachlor or bifenox granular formulated at 1.0-2.0 kg ai/ha are applied into seedbeds for 7-8 days after sowing, in some regions, Post-emergence application is not practical because of the high toxicity of chemicals to young rice seedlings. Some post-emergence herbicides are highly toxic to rice seedlings if applied less than 25 days after sowing.

For broadleaf weeds and sedges control in rice seedbeds, spraying with either 2,4-D or MCPA, when the air temperature is somewhat low, will produce some onion-leaf symptoms on the seedlings for 10 days after treatment. Japonica cultivars may be more sensitive than indica cultivars. Nowadays, these phenoxy herbicides for dicotyledonous weeds have been replaced by bentazon or dymron for use on sedges. Bentazon liquid (48%) for annual broadleaf and sedge control in seedbeds, can be applied at the rate of 750-1500 g ai/ha diluted in an appropriate volume of water and spraying at any time after weed emergence. Dymron w.p. 50% is only used for controlling annual and perennial sedges and applied at 2500-4000 g ai/ha by soil incorporation before levelling.

WEED MANAGEMENT IN TRANSPLANTED RICE FIELDS

An integrated system of weed control is being adopted in transplanted rice fields by many rice farmers.

Weed control in rice culture involves two basic measures: puddling and flooding of paddy fields and subsequent control of weeds by manual means or herbicide application. In south and southeast Asia as well as developing countries in other continents, mechanical and hand weeding may produce high rice yields but farm labour for rice weed control consumes about one-third to one-half of total labour input.

Puddling the soil after land ploughing may reduce the broadleaf weed damage. The number of weeds in transplanted rice fields declines as the number of pre-planting harrowings increases.

Good water management after transplanting is a well-known measure for weed control. Many weeds will not germinate under flooded conditions. After rice transplanting, a deep water layer maintained for as long as possible can suppress weeds; shallow water and alternating flooding and drying are favourable to weed growth. Maintaining a depth of 10-20 cm water can reduce infestations of annual grass weeds such as *Echinochloa crus-galli*, however in some areas, it may increase aquatic weed problems. Although the crop requires alternate flooding and draining, continuous flooding in paddy fields at more than 15 cm depth maintained during crop growth can reduce competition from annual grass weeds.

By planting rice at close distances between hills, the crop rapidly forms crop canopy shading weeds. At a density of 100 to 200 plants/m² rice competes strongly with weeds. Yield losses are less with rice planted in hills at 20 cm x 20 cm compared with 25 cm x 25 cm spacings.

In southeast China, farmers used to transplant old tall rice seedlings in irrigated paddy fields to suppress weed growth, due to the fact that old seedlings at the 5-6 leaf stage have more tillers than younger ones and begin jointing early. In transplanted rice, fertiliser application should be done after weeds are removed.

Despite some disadvantages, the use of a rotatory weeder and hand weeding may be the most effective methods for controlling annual and perennial weeds. Animal-drawn spike-tooth harrows, machetes, narrow spades, hoes and other mechanical devices are used for weeding in transplanted rice fields. In some developed regions, manual rotary weeders or powered by a small gasoline engine and spike-tooth harrows drawn by animals are used. Two times of hand weeding at about 20 days and 40 days after transplanting will be sufficient to control weeds, save labour hours and increase rice yields.

Using a push-type rotary weeder or spike-tooth harrows in rice fields is only feasible when rice seedlings are planted in rows. One pass over the transplanted rice fields between 10 to 15 days after transplanting is desirable, if weeding were done late, planting spacing and the width of the rotary weeder would not be compatible, the rotary weeding cannot be used. Rotary weeders are not suitable for control of creeping grasses. Hand pulling is needed to eliminate remaining weeds after manual or powered rotary weeder is used.

More than 60 herbicides are used for transplanted paddy fields, some of them are formulated as mixtures of two or three active ingredients. Nitrofen, chlornitrofen, propanil, thiobencarb, butachlor, pendimethalin, molinate, oxadiazon, bensulfuron-methyl, bentazon, MCPA, 2,4-D-butyl, quinclorac, dimepiperate, pyrazosulfuron-ethyl, paraquat, oxyfluorfen, glyphosate-amine, dymron and the mixtures of thiobencarb plus simetryn, dimethametryn plus piperophos, molinate plus simetryn, butachlor plus bensulfuron-methyl, MCPA plus bensulfuron-methyl, MCPA plus simetryn, MCPA plus molinate and simetryn, and MCPA plus thiobencarb and simetryn are used worldwide.

Salts, esters or amine-compounds of MCPA and 2,4-D have been used in south and southeast Asia for Post-emergence control of annual broadleaf weeds and sedges in transplanted rice for more than thirty years. Sodium salts of MCPA and 2,4-D are the most common formulations as they are water-soluble powders or water-soluble liquids and control *Monochoria vaginalis*, *Sphenoclea zeylanica* Gaertner, *Cyperus difformis* and other annual sedges.

The selective herbicide, propanil is used for controlling *Echinochloa crus-galli*, *Echinochloa colona* (L.) Link and other species of *Echinochloa* or some kinds of annual grasses. Propanil can only be applied for post-emergence control of *Echinochloa* spp. at 1-2 leaf stage. However it can be applied in combination with other herbicides to broaden the weed spectrum and controlling older seedlings of *Echinochloa* spp.

Thiobencarb is more selective and safer to rice. It has many advantages, being high selectivity between rice and grasses, compatible with insecticides and fungicides, with a wide application period and broad weed spectrum. It can be applied under various climatic conditions and at the period from weed pre-emergence to soon after emergence.

Butachlor is a highly selective herbicide used in many tropical and subtropical areas for controlling annual grass weeds, broadleaf weeds and some sedge species. It can be applied pre- and post-emergence to weeds in transplanted paddy fields.

Molinate is a special herbicide for controlling seedlings of *Echinochloa* spp. at the 1-4 leaf stage.

Oxadiazon is the most effective herbicide to *Echinochloa* spp. It can be used at pre- and post-emergence.

Bensulfuron, if applied at the appropriate time, is a more effective herbicide for sedge and broadleaf weed control.

Bentazon is highly selective and effective against perennial sedges such as *Scirpus planiculmis*, broadleaf weeds such as *Monochoria vaginalis*, *Alisma* spp. and *Commelina* spp.

Mixtures of two or more herbicides in transplanted rice fields to broaden the weed spectrum have been evaluated. About 30 herbicides used in combinations could reduce the rates of individual products while increasing the number of target weed species. In past years, nitrofen was mixed with PCP, thiobencarb, butachlor or molinate used as pre-emergence herbicides. Nowadays, bentazon with propanil or with MCPA as post-weed-emergence herbicides are used for controlling *Monochoria vaginalis*, *Alisma orientale*, *Cyperus difformis* and other broadleaf weeds or sedges. Mixtures based on thiobencarb, molinate, butachlor combined with s-triazine herbicides such as simetryn have given good weed control in transplanted rice. A new sulfonyl herbicide, bensulfuron, has shown excellent activity on *Scirpus planiculmis* and some broadleaf weeds but is not effective on grass weeds. Using butachlor in a tank mixture with bensulfuron can produce satisfactory results.

Most herbicides are formulated as emulsifiable concentrates, diluted with a considerable volume of water are applied by pre-emergence or post-emergence spraying. Some herbicides in dust form can be mixed with sand or dry soil and distributed by hand. Soil-applied herbicides such as chlornitrofen and thiobencarb are usually formulated in granular form being conveniently distributed in transplanted rice with standing water by hand broadcasting or with a granular applicator. The power pipe duster is also used for applying granular herbicides. Granular herbicides are generally more accepted than liquid forms. Other herbicides with special application such as oxadiazon formulated in emulsifiable concentrate form, are applied directly, without diluting to the water surface in fully submerged paddy fields by swinging the herbicide container as farmers walk through the paddy fields.

The well-known non-selective and systemic herbicide, glyphosate is applied by a wiping technique for controlling weeds growing above crop canopy. The technique is practised by using an inert absorbent medium to transfer herbicide liquid from the applicator directly to the target weeds which are taller than crop plants.

CHEMICAL CONTROL IN DIFFERENT WEED POPULATIONS

Annual grass weed populations dominated with *Echinochloa* spp. in transplanted rice fields can be controlled with the timely applications of butachlor, thiobencarb, molinate, propanil, quinclorac or pretilachlor. Butachlor 60% e.c. at 900-1800 g ai/ha or thiobencarb 50% e.c. at 2000-3000 g ai/ha can be applied for 5-7 days after transplanting. Molinate 90.9% e.c. at 1500-2500 g ai/ha being more effective on 2-3 leaf *Echinochloa* spp. than thiobencarb or butachlor, can be used for older seedlings of *Echinochloa* control, but this herbicide evaporates readily from paddy soil, so it is necessary to maintain the flooded condition to a depth of 5-10 cm for 5-10 days. Quinclorac 50% w.p. is a most effective herbicide against old *Echinochloa crus-galli* seedlings sprayed at 300-400 g ai/ha after draining off the flooding water from the rice fields. Two to three days after application fields are flooded again to the depth of 3-5 cm and maintained at that for 5-7 days.

Leptochloa chinensis can be effectively controlled by pre-weed-emergence application, pretilachlor 30% e.c. at 450-600 g ai/ha applied at 4-5 days after transplanting or by post-emergence herbicides such as propanil 20% e.c. at 2000-3000 g ai/ha or thiobencarb 50% e.c. at 2000-3000 g ai/ha. They are applied after weeds are at the 1-2 leaf stage after draining off the flooding water. The fields are flooded again at 1-2 days after spraying.

Scirpus planiculmis is adapted to a wide variety of conditions including salinity. Its tubers germinate about 5-7 days after levelling the paddy fields. The proper time for chemical control is at flowering when nutrients in the tubers have been exhausted and young plants have not formed tubers. Plants growing from seeds are easily killed by herbicides. For controlling *S. planiculmis*, the application of dymron 50% w.p. at the rate of 2500-4000 g ai/ha by soil incorporation before levelling the paddy fields or bensulfuron 10% w.p. at 15-30 g ai/ha by pre-emergence treatment at 5-7 days after transplanting. The diethylamine salt or 72% butyl ester of 2,4-D at the rates of 500 g ai/ha or 1000 g ai/ha respectively can be applied for controlling *S. planiculmis* on flowering stage, and 48% bentazon liquid can be applied at the rate of 750-1500 g ai/ha giving good control. The mixture of bentazon and 2,4-D at 1000 g and 500 g ai/ha respectively is more effective than applying bentazon alone at 2000 g ai/ha to control *S. planiculmis*.

For weed populations dominated by *Cyperus serotinus*, dymron 50% w.p. at the rate of 2500-4000 g ai/ha mixed with dry soil or sand incorporated into soil before levelling can achieve very good control results. Pyrazosulfuron-ethyl 10% w.p. mixed with dry soil or sand broadcast at the rate of 22.5-30 g ai/ha into flooded paddy fields 3-5 days after transplanting, or Ordram® 78.4% e.c. (a mixture of three herbicides containing 60% molinate, 12% simetryn and 6.4% MCPB-ethyl ester) at the rate of 1500-2500 g ai/ha sprayed onto the target weeds or mixed with dry soil or sand then broadcast into the flooded paddy fields 10-20 days after transplanting and maintaining water layer at 5 cm depth for 5-7 days can give satisfactory results. Bentazon (48%) liquid alone at the rate of 1500 g ai/ha or bentazon (48%) liquid at 750 g ai/ha combined with 20% MCPA-Na liquid at 450-900 g ai/ha diluted with water used as post-weed-emergence application can be sprayed onto the target weeds before rice jointing stage.

Potamogeton distinctus is one of the hard-to-control perennial weeds propagating by overwinter buds depending upon their stored nutrients. Application should be carried out while the floating leaves of weeds have become greenish and the stored nutrients have been exhausted. Bensulfuron 10% w.p. applied at 20-30 g ai/ha 7-10 days after transplanting or Avirosan® 50% e.c. (a mixture of 10% dimethametryn and piperophos 40% e.c.) and 5.5% Avirosan® granules

(a mixture of 1% dimethametryn and 4.5% piperophos) at the rates of 1200-1500 g ai/ha applied 10-16 days after transplanting can achieve the most effective results. Prometryn 50% w.p. at 500 g ai/ha or 25% simetryn w.p. at 350-700 g ai/ha applied 30-40 days after transplanting produces good results in China, but if these herbicides are applied under hot air temperatures they will occasionally cause injury to rice.

Monochoria vaginalis is an annual broadleaf weed and highly competitive. Many pre-emergence herbicides can be used to control this weed but several cohorts of seedlings emerge with rapid growth, so post-emergence herbicides must be applied several times. Bentazon (48%) liquid applied at 1500 g ai/ha after the weed has emerged at 2-3 leaf stage can give effective control.

Sagittaria pygmaea, *S. natas* and *S. sagittifolia* L. are difficult-to-control weeds in paddy fields. In transplanted rice fields, emergence peaks are between 10 and 20 days after transplanting. Bensulfuron 10% w.p. at the rate of 20-30 g ai/ha can be applied just before or within one week after transplanting. Bentazon (48%) liquid combined with 20% MCPA-Na liquid at the rates of 750 g ai/ha respectively applied by foliar spraying may achieve effective control.

Bidens frondosa L., *B. tripartita* L. and *B. maximowiziana* can be controlled at the young seedling stage. Bentazon (48%) liquid at 1500 g ai/ha or 20% MCPA-Na liquid at 750 g ai/ha can be applied by spraying after the field has been drained for 1-2 days. Ordram® 78.4% e.c. at the rate of 2000-3000 g ai/ha mixed with dry soil or sand can be broadcast into flooded fields for 15-20 days after transplanting.

Weed populations of *Echinochloa crus-galli* and *Potamogeton distinctus* should be controlled with a tank mixture of butachlor 60% e.c. and bensulfuron 10% w.p. applied at the rates of 900-1500 g ai/ha and 20-30 g ai/ha respectively 5-7 days after transplanting. The tank mixture of molinate 90.8% e.c. at 1500-2000 g ai/ha and bensulfuron 10% w.p. at 20-30 g ai/ha or molinate 90.8% e.c. at same rate combined with simetryn 25% w.p. at 280-380 g ai/ha can be applied to *Echinochloa* spp. at the 2-3 leaf stage 10-15 days after transplanting then maintaining flooding water at 5-10 cm depth for 5-10 days.

To control weed populations of *Echinochloa crus-galli* and *Potamogeton distinctus*, Avirosan® 50% e.c. (a mixture of 40% piperophos and 10% dimethametryn) or Avirosan® 5.5% granules (a mixture of 4.5% piperophos and 1% dimethamethyn) can be used at the same rate of 1500-2000 g ai/ha by spraying or broadcasting respectively, 10-15 days after transplanting. However this herbicide formulation may cause phytotoxicity to rice under high air temperatures (>30 °C). Other possibilities are spraying tank mixtures of thiobencarb 50% e.c. at 2000 g ai/ha and simetryn 25% w.p. at 300 g ai/ha or the granular formulation containing 5% butachlor at 1500 g ai/ha and 0.3% simetryn at 90 g ai/ha by broadcasting into flooded rice fields 7-10 days after transplanting. In temperate regions where *Echinochloa* spp. and *Scirpus* spp. emerge at the same time, a tank mixture of butachlor 60% e.c. at 900 g ai/ha and pyrazosulfuron-ethyl 10% w.p. at 15-20 g ai/ha applied by spraying or by mixing these herbicides at a same rates with dry soil or sand broadcast into flooded fields 5-7 days after transplanting and maintaining water depth at 3-5 cm. Molinate 90.8% e.c. at 1500-2000 g ai/ha combined with pyrazosulfuron-ethyl 10% w.p. at 15-25 g ai/ha diluted with an appropriate volume of water can be sprayed or mixed with dry soil or sand and then broadcast into flooded water at two-leaf stage of *Echinochloa* spp. The field water level should be kept at a depth of 5-10 cm. Dimepiperate 50% e.c. at 1200-2000 g ai/ha combined with bentazon 48% liquid at 750-1200 g ai/ha diluted with an appropriate volume of water can be sprayed before the two leaf stage of *Echinochloa* spp. after transplanting.

Quinclorac 50% w.p. at 300 g ai/ha combined with bentazon 48% liquid at 750-1200 g ai/ha or quinclorac 50% w.p. at 300 g ai/ha combined with MCPA-Na 56% at 400-450 g ai/ha can be sprayed at the 2-3 leaf stage of *Echinochloa* spp. Water is drained from the paddy fields before spraying, and two days later, the fields should be reflooded maintaining the water layer at the required depth for 5-7 days.

Paspalum distichum is a creeping perennial grass with an adventitious root system and rhizomes. It may be controlled with non-selective herbicides such as glyphosate or paraquat before rice transplanting and through land preparation. Glyphosate 10% liquid or paraquat 20% liquid used alone (each at the same rate of 1500 g ai/ha) can effectively control *P. distichum*, other annual grasses, broadleaf weeds and sedges, but if sprayed with paraquat will regrow faster than with glyphosate application. When the combination of glyphosate followed by paraquat was applied, the best results were obtained. *Leersia hexagon* can be controlled by treatment with glyphosate at 1500 g ai/ha or dalapon at 8000 g ai/ha immediately after harvesting or by treatment with TCA at 2000 g ai/ha in the winter.

Weed populations of *Scirpus planiculmis*, *Cyperus serotinus*, *Bidens tripartita* and other *Bidens* spp. are a perennial weed community; each of them may be the dominant species. In recent years, *Bidens tripartita* has become more important, especially under the water shortage in paddy fields in some Asian countries, such as China. Bentazon 48% liquid at 750-1500 g ai/ha plus 56% MCPA-Na at 400-450 g ai/ha or propanil 20% e.c. at 1500-3000 g ai/ha plus 56% MCPA-Na at 420-500 g ai/ha and pyrazosulfuron-ethyl 10% w.p. at the rate of 30 g ai/ha can be applied for 7-10 days after transplanting.

Echinochloa spp., *Scirpus* spp., *Potamogeton* spp. and *Sagittaria* spp. weed populations can be controlled with the mixture of quinclorac 50% w.p. at 200-300 g ai/ha plus 56% MCPA-Na at 500 g ai/ha and bentazon (48%) liquid at 1000 g ai/ha sprayed post-emergence at 2-3 leaf stage of *Echinochloa* spp., 10-20 days after transplanting. Ordram® 78.4% e.c. at the rate of 2400-3000 g ai/ha can be used for this weed population control at the same application time. Algal weeds can be controlled by applying $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ at the rate of 200-300 g ai/ha per day for at least a week. Triphenyl tin acetate at 1000 g ai/ha and sodium ethylene bisdithiocarbamate at 6000 g ai/ha are also used for algal control in paddy fields.

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CHAPTER 6

WEED MANAGEMENT IN UPLAND RICE

WEED MANAGEMENT IN UPLAND RICE

Keith Moody

INTRODUCTION

About 13% (19.3 million ha) of the total rice area of the world is planted to upland rice but this accounts for only 4-5% of the world production; yields average about 1.3 t/ha. Upland rice farmers are among the poorest of the world's farmers and have been largely unaffected by recent advances in agricultural productivity that have benefited many lowland rice producers. Yields of upland rice are low because of problems such as lack of suitable cultivars, erratic water supply and poor weed control.

In upland rice, weeds are the greatest yield-limiting constraint. The losses caused by and the cost of control of weeds are among the most expensive items of upland rice production. Weeds rank highest in terms of potential output value foregone (Herd 1991). The extent and value of damage vary greatly from year to year depending on such factors as weed species, soil conditions and climate.

Major weed species in upland rice include *Ageratum conyzoides* L., *Amaranthus spinosus* L., *Commelina benghalensis* L., *Cynodon dactylon* (L.) Pers., *Cyperus rotundus* L., *Digitaria* spp., *Echinochloa colona* (L.) Link, *Eleusine indica* (L.) Gaertn., *Portulaca oleracea* L. and *Rottboellia cochinchinensis* (Lour.) W.D. Clayton. Parasitic weeds (*Striga* spp.) are becoming increasingly important in Africa and Madagascar.

The removal of weeds is one of the greatest problems for a rice farmer. The success or otherwise of the rice crop depends on this operation (Subbiah Pillai 1958). Weeding is the major bottleneck in the rice agricultural calendar and limits the area of land that can be cropped. In some cases, the available labour is limited and cannot cope with the weed problem; as a result, fields are abandoned.

YIELD LOSS

Protecting the rice crop from weed infestation is one of the more important and effective yield-increasing operations. In the absence of efficient weed control, other inputs such as high-yielding, disease and insect resistant cultivars and fertilisers will be useless. Weed competition and corresponding yield losses are usually greater in upland rice than in other rice production systems (Moody 1983). The limited data available show that production losses can reach 30-40% for fields that are poorly weeded (Anon. 1988); yield losses can be almost total if there has been no weed control. Elliot and Moody (1987) reported that an additional weeding within 8 weeks after crop emergence resulted in yield increases of 43-80%.

CRITICAL PERIOD OF COMPETITION

During the cropping period, there is a particular length of time, the critical period of competition, during which the crop is very sensitive to competition and the presence of weeds above a certain density will cause a significant yield reduction. Weeds should be controlled within this period. The precise time and duration of the critical period depend on many factors such as the weed flora, growth characteristics of the rice and the weeds, cultural practices and environmental factors (Moody 1977b). Weeds that emerge before or with the crop are far more competitive than those that emerge 1 to 2 weeks later than the crop. If weed growth can be prevented from the initial slow-growth phase of the crop until it enters the fast-growth phase,

the influence of weed competition can be greatly reduced. The maximum tillering stage and the stage before rice heading are the most sensitive to competition from weeds resulting in reduction in the number of productive tillers and in the number of panicles causing severe grain yield losses.

It is often during the period from 2 to 6 weeks after emergence that upland rice yield is lost due to competition from weeds (cf. Ghosh *et al.* 1975; Sahai *et al.* 1983; Anon. 1985; Behera and Prusty 1992); the longer weeds compete with the crop, the lower the grain yield. The end of the critical period of competition is reached when the crop's canopy is sufficiently developed to suppress emerging weeds. At this time, a uniform rice stand is important to avoid the establishment of late-emerging weeds in gaps left by irregular stand establishment.

WEED CONTROL METHODS

Most cultural practices may be regarded as means of weed suppression and an increase in their efficiency would contribute to better weed control (Anon. 1952).

Burning

Burning is essential under traditional farming systems to rid the land of the great mass of plant debris following land clearing or a fallow period, in order to obtain a suitable seedbed for cropping (Kang and Sajjapongse 1980). Burning is known to have multiple effects such as increase in phosphate, silicate and cation levels of the surface soil from the addition of ash, loss of part of the nitrogen and sulfur from organic plant residues, increase in soil pH and reduction in soil microbial population from direct heating of the immediate soil surface (Nye and Greenland 1960; Laudelout 1964).

Weeds which are in the process of germinating or have already germinated are killed by fire. Most dry seeds, however, are more tolerant of high temperatures than are plant tissues and often require prolonged exposures to kill them (Schlesselman *et al.* 1985). Moody (1991) reported that burning promoted the germination of *Mucuna pruriens* (L.) DC. and *Mimosa invisa* Mart. *M. invisa* has a hard seed coat and high dormancy; during burning the seed coat bursts, imbibition takes place and germination begins (Eussen and Wirjahardja 1973).

Cover Crops

Shifting cultivation is a term used for an agricultural system which is still widely practised in the humid tropics. The system involves farming a piece of land for a short period following clearing until declining yields or increasing weed intensity force the farmer to abandon the land to fallow. Generally, the land is fallowed for a longer period than it is cropped (Moody 1975). During the fallow period the abandoned crop area is recolonised by native herbaceous, shrub or tree species or by adventive species (Norman 1979). If population pressure or lack of alternatives shorten the period of regrowth or extend the cropping period beyond that for which a particular soil and topography are best suited, the system deteriorates. The forest fails to regenerate and the land may be taken over by vegetation not adaptable to the system. In southeast Asia, *Imperata cylindrica* (L.) Raeuschel covers much of the land that has been lost to the system (Barker and Herdt 1985).

Jurion and Henry (1969) reported that *I. cylindrica* was successfully smothered by legume cover crops. In order of effectiveness, these were tropical kudzu [*Pueraria phaseoloides* (Roxb.) Benth.], stylo and calopo (*Calopogonium mucunoides* Desv.). However, legumes will not establish in the presence of *I. cylindrica* if they are broadcast on unploughed land; the seedlings

of many introduced grasses and legumes make slow initial growth and do not compete satisfactorily with weeds. The land must be ploughed to partially control the weed. Phosphate may also need to be applied. Other promising cover crops include mucuna [*Mucuna pruriens* (L.) DC. var. *utilis* (Wight) Burck], centro (*Centrosema pubescens* Benth.), phospho (*Phosphocarpus palustris* Desv.) (Akobundu 1992).

Desiccation

Ploughing at the end of the rainy season brings many of the roots, rootstocks and vegetative propagules of perennial weeds to the soil surface where they are killed by desiccation. Additional cultivations can then be carried out during the dry season, if necessary, to control persistent weeds. Final land preparation can be done immediately after the start of the next rainy season so that one or two flushes of weed seedlings can be destroyed before the crop is planted or the seedbed might be in such a condition that the crop can be seeded without further land preparation.

Land Preparation

The success of upland rice depends on the thoroughness of land preparation (Camus 1921). A poorly prepared field does not provide a suitable medium for optimum plant growth. Failure of some rice seeds to germinate, uneven crop stand and poor crop growth result in delay in canopy closure or vacant spaces providing opportunities for weeds to grow.

Land is prepared mainly by animal-drawn implements or manually. Ploughing for seedbed preparation is intended to destroy existing weeds and to stimulate germination of weed seeds in the top soil layers so that resulting weed seedlings can be killed by harrowing before the crop is planted. Poor land preparation is a major factor in increasing weed infestations (Allnut 1942; Abeyaratne 1956; Biswas and Khan Bassi 1982).

Ploughing Depth

Uichanco (1959) reported that increased tillering, plant height, crop yield and better weed control were obtained with deep ploughing (20-25 cm). Other authors (Pande and Bhan 1966; Curfs 1975; Singh *et al.* 1988) have also shown the effectiveness of deep ploughing in reducing weed biomass. Deep ploughing may bury weed seeds at a depth that prevents germination but, at the same time, it may also expose other, once deeply buried weed seeds to conditions favourable for germination (Stoskopf 1985).

Stale Seedbed

Weed problems in upland rice may be reduced by allowing successive flushes of weeds to emerge following rainfall and controlling them either with a shallow cultivation or by the application of a nonselective, nonresidual herbicide. The herbicide should be applied or cultivation should be done when most of the weed seeds in the surface soil have germinated and the weed seedlings have reached the two- to five-leaf stage. Seeding should take place as soon as possible after completion of these operations. Later weedings may be reduced or delayed by using this method of land preparation.

Blind Cultivation

Cultivation after planting but before seedlings emerge is sometimes practised to break the soil crust creating conditions favourable for rice emergence and stand establishment and to kill young weed seedlings. This is commonly done with a spike-tooth harrow or other implements with finger-like tines that lightly penetrate the soil.

Cultivar Grown

The crop is the most important agent in weed control. The competing power of a crop against weeds is relative to and conditional upon factors such as cultivar grown, land preparation, row spacing, seeding rate, fertiliser rate and application time, time of planting, time of weed infestation, duration of weed control and time of weeding.

Upland rice farmers who are dependent on manual weeding for weed control cultivate tall (1.3-1.6 m) cultivars which are more competitive with weeds than the short, modern cultivars. Garrity *et al.* (1992) identified several cultivars which were highly competitive against weeds; weed weights for the five most competitive cultivars were 75% lower than those of the five least competitive cultivars. Rice plant height was the character most strongly related to low weed weight, with statistically significant correlations ranging from -0.76 to -0.88 across weeding levels and years. Leaf area index was also negatively correlated with weed weight but tiller number was not. The minimum plant height to adequately suppress weeds was 1.00 to 1.15 m.

Competitiveness alone is not an adequate weed control method. Although powerful, it needs to be integrated with other techniques (Minotti and Sweet 1981). Using a competitive cultivar and enhancing its competitive ability through good crop husbandry can minimise weed control inputs needed to achieve optimum yields (Harwood and Bantilan 1974).

Garrity *et al.* (1992) concluded that the choice of a relatively competitive cultivar may provide the practical equivalent of one or two hand weeding. The additional cost to obtain a comparable level of weed control with semi-dwarf cultivars may be a significant factor underlying their lack of adoption by farmers.

Canopy Closure

The earlier the canopy closes, the lower the loss of nutrients and water due to weed competition (Moody 1991). The rate at which the canopy closes depends on climatic conditions, distance between rows, cultivar grown and amount of fertiliser applied. Under upland conditions, it may take up to 45 days for the canopy to close. A topdressing of fertiliser after the first weeding will boost rice growth and canopy closure will be earlier.

Seeding Rate

High plant density can suppress weed competition in upland rice (Kawano *et al.* 1972; ARS 1981; Kehinde 1985; Gassaver and Fion 1988).

Intercropping

Intercropping refers to the growing of two or more crops simultaneously on the same piece of land. Increased productivity, insurance, reduced weed growth, reduced pest problems and reduced labour are reasons given for intercropping (Moody 1977a).

In Laos, Shelton and Humphreys (1972) successfully established stylo [*Stylosanthes guianensis* (Aubl.) Sw. cv. Endeavour] in upland rice up to 35 days after planting to provide protein feed for livestock after harvesting the rice grain without detrimental effect on rice yield. Sowing molasses (*Melinis minutiflora* Beauv.) and guinea (*Panicum maximum* Jacq.) grasses with the rice crop decreased rice yield by 19%; rice yield was unaffected if stylo and grasses were sown together. By using this establishment technique, weed generation may be partly controlled by a pioneering pasture legume, better animal use of low quality crop residues becomes feasible and soil protection and fertility accretion may result. Simultaneous undersowing of upland rice with

stylo at Khon Kaen, Thailand did not affect vegetative growth of rice but reduced grain yield by 19% but not if stylo undersowing was delayed for 10 days (Shelton and Humphreys 1975).

Elliot *et al.* (1992) reported that weed growth was less when cowpea [*Vigna unguiculata* (L.) Walp.] was intercropped with upland rice than when upland rice was grown alone due to rapid canopy formation of the cowpea crop. Sengupta *et al.* (1985) reported similar results with upland rice and blackgram (*Vigna mungo* L.).

Alley Cropping

Alley cropping is a system in which food crops are grown between hedgerows of perennial leguminous, woody shrubs and/or grasses (Kang *et al.* 1984). Advantages of alley cropping are that farmers can grow a crop, a green manure, a mulch and a fodder simultaneously (Kang and Duguma 1985). Weed and erosion control, as well as provision of fuelwood and livestock feed, are also important attributes of the system (Wilson and Kang 1981). Weeds are reduced by the shading effect of the hedgerow species (Newman 1985; Jama *et al.* 1991), by the prunings placed on the soil surface as a mulch (Yamoah *et al.* 1986; Budelman 1988) and possibly by leachates from the decaying mulch (Jama *et al.* 1991). A shift in the weed species from grasses and sedges (*C. rotundus*) to broadleaved species which are easily removed has also been reported (Jama *et al.* 1991).

Fertiliser Application

Weed growth is usually stimulated by applications of nitrogen and phosphorus. High fertiliser levels can cause proportionately greater weed growth than increase in crop yield. Weed control is, therefore, more important at high than at low soil fertility.

Fertiliser application should be timed to prevent weed proliferation and yet obtain maximum benefit for the crop. When rice plants are small, they do not require nor can they use much nitrogen. Nitrogen application should be delayed until the weeds have been removed (Moody and Mian 1979), otherwise weed competition may increase to such an extent that crop yield may be lower than if no fertiliser had been applied. Moody (1981) reported that, in most cases, yields of unweeded fertilised treatments were considerably lower than those of weeded treatments to which no fertiliser had been applied.

A considerable portion of the added nitrogen may be used by weeds (N uptake by weeds is negatively correlated with N uptake by rice), thus higher amounts of nitrogen will be needed to obtain maximum rice yields (Smith 1960). By controlling weed growth, it is possible to maintain crop production at a lower level of nitrogen fertilisation (Moody 1981).

In upland rice, fertilisers should be applied immediately after weeding (Dobby 1955; John and Kalode 1981). If weeds are not controlled before fertiliser is applied then weed competition increases. If weeds are not adequately controlled then fertiliser should not be applied (Sankarama 1986).

In Aungban, Myanmar, upland rice farmers mix fertiliser (urea + triple superphosphate) with seed and drill the mixture into furrows to reduce costs (Fujisaka *et al.* 1992) and possibly to make the fertiliser more available to the crop than the weeds, thus reducing weed growth.

Manual Weeding

Manual weed control methods are usually used in most upland rice fields and farmers typically invest several hundred hours per hectare in these operations. One weeding, no matter how well timed, will not provide season-long weed control in upland rice. When upland rice fields are moderately infested with weeds, two weedings, one as early as possible (10-14 days after emergence) and the second 20-25 days later, are generally sufficient. However, when weed growth is severe, three timely weedings may be necessary to minimise yield losses caused by weed competition (Moody 1991).

Inter-row Cultivation

Inter-row cultivation is also practised in some areas but its effectiveness is highly dependent on the uncertain occurrence of suitable soil moisture conditions for field operations (Garrity *et al.* 1992). Heavy rains soon after planting prevent the use of inter-row cultivation on medium to heavy textured soils. Also, if it rains soon after inter-row cultivation, the weeds may quickly re-establish with little or no apparent injury. Grasses completely smother the rice crop in fields where tillage operations have not been successful.

A traditional system of weed control in upland rice in Batangas, Philippines is to pass a spike-toothed harrow, or *kalmot*, diagonally across the rows from 10 to 20 days after emergence. This is followed by one or two inter-row cultivations with a *lithao* (wooden furrower). These operations uproot weeds, bury them or disturb their roots causing them to die or be greatly weakened. Crop injury and mortality are countered by using high seeding rates. Weeds that survive are usually removed manually using a *dulos* (native trowel).

Crop Residues

Khan and Vaishya (1992) reported that residues of rice cv. Sarjoo-52 reduced the population of *E. colona* by 40% and broadleaved weeds by 56%; biomass production was reduced by 39 and 64%, respectively.

Herbicides

Many countries are experiencing rising labour costs and a shortage of labour, accompanied by a high labour requirement for controlling weeds in rice. Chemical weed control is consequently taking on increasing significance for rice growing and is viewed by many farmers to be a problem solver.

Pre-emergence herbicides that have been reported to control weeds effectively in upland rice include butachlor, oxadiazon, oxyfluorfen, pendimethalin and thiobencarb. Post-emergence herbicides that control grass weeds effectively include propanil and fenoxaprop-ethyl, 2,4-D, MCPA and bentazon have been used for broadleaved weed and sedge control. Proprietary mixtures or herbicide combinations that have performed well under upland conditions include oxadiazon + propanil, piperophos + propanil, pretilachlor + dimethametryn and bentazon + MCPA.

Herbicides have proven effective in some cases for weed control in upland rice but unfortunately they are not sufficiently reliable under a wide range of environmental conditions. Herbicide use is only a partial substitute for hand-weeding and has been used as a labour-saving device rather than a means to enlarge the area cultivated (Cramb 1984).

CONTROL OF *STRIGA* SPP.

There is no single method presently available to control *Striga* which is both effective and economically feasible. The best solution is an integrated approach that includes a combination of all available methods. Control measures must involve a long-term integrated approach with soil improvement/ conservation being the end point (Mboob 1989).

The use of an appropriate trap crop for one or more years in rotation with a resistant/tolerant cultivar will go a long way to reduce the number of *Striga* seeds in the soil. This may be enhanced by the use of supplementary weed control measures, such as hand pulling, hoeing or application of a herbicide, to destroy the *Striga* plants. Integration of weeding with high urea application, appropriate sowing date and effective control of weeds which may serve as alternate hosts, will further enhance the long-term control of *Striga*. However, unless preventive measures are taken, reinfestation may occur even when effective control has been achieved. Reinfestation can be averted through effective seed quarantine, equipment hygiene, weed free irrigation water and the use of composted farmyard manure. *Striga* seeds have usually lost viability in composting and farm animals should have been prevented from feeding on flowering plants (Lagoke *et al.* 1991).

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CHAPTER 7

WEED MANAGEMENT IN DIRECT SEEDED RICE

WEED MANAGEMENT IN DIRECT SEEDED RICE

Nai-Kin Ho

INTRODUCTION

Direct seeded rice is conveniently classified into wet seeded and dry-seeded rice culture. When rice is wet-seeded, land preparation is essentially the same as that of transplanted rice. After ploughing, raking and puddling, the rice fields are levelled to avoid ponding of water. Pre-germinated rice seeds are normally broadcast by hand or machine on a saturated soil surface. Prior to seeding, excess water is drained from the field to ensure uniform seedling establishment.

When rice is dry-seeded, the rice fields are ploughed when dry. The broadcast non pre-germinated seeds are subsequently incorporated into the ground without any flooding. The crop begins its life cycle as a dry land crop, but as the rainy season progresses, water accumulates in the fields, and the crop usually completes its life cycle as a wet-land crop.

The recent transformation in crop establishment technique from transplanted to direct seeded rice cultivation in Thailand, Philippines and Malaysia, has resulted in dramatic changes in the types and intensity of weed infestation. Studies conducted in Malaysia clearly showed that the direct seeding technique caused weed populations to shift from the less competitive broadleaves and sedges to difficult to control grasses (Baki 1982; Ho 1984; Azmi and Supaad 1986; Lo 1988). A much wider range and intensity of weed problems can be expected with further expansion of direct seeding.

Moody (1983) reported that weed competition is greater in wet seeded rice than in transplanted rice. This is because of the similarities in age and morphological characteristics of grassy weeds and rice seedlings. Yield losses due to uncontrolled weed growth were on average 9% higher in wet seeded rice than in transplanted rice in trials conducted at IRRI over the past 20 years. Weeds are a more serious problem in dry-seeded rice than in other cultures. Lack of water is the main factor which triggers increased weed density and competition in dry-seeded rice.

This chapter outlines the various methods used in weed management for direct seeded rice in Asia. Other aspects covered in this chapter include the integrated approach, as well as future needs in research and technology development under direct seeded conditions.

AGRONOMIC PRACTICES

Land Preparation

Proper land preparation is the key to good crop establishment. Thorough land preparation reduces weed problems in direct seeded rice, while poor land preparation increases weed infestation, severity and lowers herbicidal efficacy. Conventional land preparation for effective weed control normally requires one ploughing and two harrowings. Where perennial weeds are absent, zero tillage techniques succeed without loss in crop yield (Seth *et al.* 1971; Croon 1978). However, where perennial weeds such as *Paspalum distichum* L. are present, increased tillage frequency is essential to minimise weed populations. *P. distichum* consistently declined in direct seeded rice as the number of harrowings increased (De Datta 1981).

Curfs (1976) found less weed growth on soils that were ploughed deep and rotovated with a high-powered tractor than those that were shallow-ploughed or zero tilled.

In China, intense land preparation by roto-tilling and maintaining rice fields as a clean fallow during the dry season can control weed growth effectively in dry-seeded rice; additional advantages are soil-moisture conservation and earlier planting at the onset of the rainy season (Zandstra *et al.* 1977).

Field studies on the growth of *Echinochloa stagnina* (Retz.) P. Beauv., a perennial grass in the Muda area of Malaysia revealed that rice fields which were prepared with only one round of dry rotovation were most severely infested by *E. stagnina*. The rotary cultivator chopped up the stolons of *E. stagnina* into segments. The spread of these segments were later facilitated by the land levelling process carried out by the tractors equipped with rear buckets. However, when the rice fields were rotovated twice under the inundated condition with thorough puddling, many severed stolons of *E. stagnina* were embedded in the soil and submerged in standing water. The sprouting capacity of *E. stagnina* was drastically reduced. Thorough soil puddling and regular weeding along the dykes and levees kept *E. stagnina* under control (Ho and Itoh 1990). Another study in the Muda area on *Marsilea minuta* L., a perennial fern, indicated that land levelling under wet field conditions aggravated the *Marsilea* problem by dispersing the rhizomes over the fields, whilst dry ploughing and dry land levelling exposed the rhizomes to the hot sun and reduced *Marsilea* infestations. In the wet season, rotovation followed by two rounds of raking, resulted in lower *Marsilea* density than with only one round raking (Ho 1985).

Moody (1983) reported that the most important effects on weed growth in rice come from puddling and good water control. Puddling buries the weeds in the lower layers of mud where they are decomposed by anaerobic micro-organisms to form ammonium compounds which could be used directly by wet-seeded rice. Remarkable reductions in weed infestations have been observed when fields were puddled twice at 15-day intervals. Puddling enhances both crop yield and water use efficiency in direct seeded rice.

Levelling of the field is more important in wet-seeded rice than in transplanted rice. This is because under direct seeded conditions, developing rice seedlings can be killed or greatly retarded in their growth when ponding of water occurs (Moody 1977).

Seeding Rates

Close spacing can minimise weed infestations and increase grain yield. The closer the rice plants are sown, the greater is the rice competition against weeds (De Datta 1988). In wet-seeded rice, the quantity of seed used is usually greater than for transplanted rice. In the Philippines, rates of 150 kg/ha are not uncommon, and rates as high as 400 kg/ha have been used (Moody 1977). Significant decreases in weed weight were observed as the seeding rate was increased from 50 to 200 kg/ha. Broadleaved weeds were the most affected by the increase in seeding rate and sedges least (Moody 1977).

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In the Muda area of Malaysia, a high seed rate (150 kg/ha) in wet-seeded rice minimises *Echinochloa crus-galli* (L.) P. Beauv. and *Leptochloa chinensis* (Roth) Nees infestation significantly compared with lower seed rates (60-70 kg/ha). However, the incidences of brown plant hopper *Nilaparvata lugens* Stal and hopper burn increased sharply in rice fields with higher seed rates (Ho *et al.* 1992).

For dry-seeded rice in non-weeded fields, increasing seeding rates or decreasing row spacing has little influence on weed suppression, probably because of the intense weed pressure (Moody 1981).

In the Philippines, when IR 36 was direct seeded in rows spaced 25 cm at rates ranging from 80 to 160 kg/ha, the method and rate of seeding had no effect on weed weight (IRRI 1980).

Moody (1982) reported that farmers in Sri Lanka used tall rice cultivars and high seeding rates (up to 700 or 800 kg/ha) to overcome the competitive effects of weeds in dry-seeded rice. At a seeding rate of 400 kg/ha, weed numbers decreased by 18% and 25% when they were growing in association with a dwarf and tall cultivars respectively. The above results were obtained by comparing with the cultivars dry-seeded at 50 kg/ha. With the dwarf cultivar, increasing the seeding rate did not decrease weed weight at harvest; but with the tall cultivar, increasing the seeding rate from 50 to 400 kg/ha decreased weed weight by 59%.

Fertilizer Application

Weed growth is stimulated by phosphorus and nitrogen applications. Azmi *et al.* (1992) reported that direct seeded rice produced significantly higher yields when nitrogen application was carried out after weed control.

Smith (1960) observed that rice that was not fertilised but kept weed free, yielded as much as rice that was heavily infested with weeds and received more than 100 kg N/ha.

In Bangladesh, addition of fertilizer (60 kg N, 40 kg P, 40 kg/ha) to dry-seeded rice without weed control resulted in a non-significant yield increase, while weed control without fertilizer addition gave significant yield increase. A further significant increase was obtained from fertilizer plus weed control.

Moody (1982) suggested that nitrogen application should be timed so as to prevent weed proliferation and yet obtain maximum benefit from the fertilizer applied. In dry-seeded rice, weed growth could be reduced when nitrogen is applied after the first round of weeding is completed.

WATER MANAGEMENT

Good water management is essential for effective weed control in direct-seeded rice. Many weeds are unable to germinate under flooded conditions. The prevention of weed growth is accomplished by the interaction of various changes in the physical, chemical and biological properties of submerged soils. Smith and Fox (1973) indicated that factors which probably inhibit growth of some weeds in the flooded soils are reduced oxygen level, accumulation of carbon dioxide and toxic gaseous products of anaerobic decomposition, as well as the presence of reduced forms of chemical radicals and gases such as methane, nitrogen oxides and sulphides. Moody (1983) reported that if fields can be kept flooded, weed populations can be reduced to a minimum level. Most weed populations decrease as the depth of the water increased. Alternate flooding and drying encourages weed growth. The longer flooding is delayed after weed emergence, the deeper the water is needed to achieve even partial weed control.

In dry-seeded rice, the rice and weed seeds germinate and grow together, with water being supplied by frequent rains during early crop establishment. Bhan (1981) stated that dry-seeded fields generally do not retain moisture at more than field capacity; this environment is ideal for

weed germination. Highest weed populations at a soil moisture content of 90% and lowest populations below 70% moisture content have been reported. Emergence and growth become increasingly poor with increased depth of submergence, when water depth reaches 10-15 cm, *E. crus-galli* stops growing and most of the plants die.

In Malaysian experiments *Echinochloa* seeds germinated readily (89-95%) in 0-1 cm of water, but germination declined to 68% at 2.0 cm water and 21% at 10 cm; poor germination (4%) was observed at 15 cm of water. However, pre-germinated *Echinochloa* seeds were more tolerant to submergence. Aquatic weeds often germinate readily under water. Newly shed seeds of *Pistia stratiotes* L. germinate under water after 20 days and float to the surface when the primary leaf emerges. Understanding of this behaviour can be utilised for weed control by flooding the fields. When the seedlings have floated, control measures can be applied (Bua-ngam and Mercado 1975).

Moody and Mian (1979) noted that weeds in dry-seeded rice are controlled better if flooding occurs soon after stand establishment. It has been recommended that dry-seeded rice can be adopted only in fields that can be flooded within 30 days of planting.

MANUAL AND MECHANICAL WEEDING

Manual weeding in direct-seeded rice is difficult and impractical. This is because the weeders damage the rice as they move through the fields. They also fail to remove some of the grasses as it is difficult to distinguish young grassy weeds from rice seedlings. Moody and Mukhopadhyay (1982) showed that manual weeding in dry-seeded rice has many drawbacks:

- . it is slow and laborious;
- . complete removal of weeds is difficult;
- . weeds regenerate from vegetative propagules left in the field
- . labour may not be available for timely weeding;
- . labour may be costly;
- . frequent hand weedings are required;
- . hand weeding is difficult in unfavorable weather;
- . crop injury may occur.

Azmi *et al.* (1992) showed that in wet-seeded rice, hand weeding could do more harm to the crop through physical damage at late crop stages. However, cutting of grassy weed panicles after anthesis could reduce the weed seed source in the subsequent seasons. This is a beneficial long term strategy to deplete weed seed banks in rice soils.

Mechanical weeding is feasible only where rice is direct-seeded in rows. Moody (1982) reported an exception in Bangladesh and West Bengal of India, where spike toothed harrows are passed through the broadcast-seeded fields at 5 to 15 days after emergence of the rice seedlings. This kills some weeds, thins the rice seedlings and loosens the soil surface. Seedling mortality is overcome by high seeding rates. Moody (1990) mentioned that farmers who practise wet-seeded rice in Iloilo province Philippines use harrowing for the control of sedges e.g. *Fimbristylis miliacea* (L.) M. Vahl, and *Cyperus difformis* L.

Manual and mechanical weeding in direct seeded rice should be used only in conjunction with other cultural and chemical methods to minimise labour requirements where appropriate.

CHEMICAL CONTROL

Moody and Cordova (1985) indicated that herbicides are the only practical and logical alternative for weed control in wet-seeded rice. Under dry-seeded conditions, higher yields also result from herbicides used to provide timely weed control.

Optimum herbicide rates are dependent on cultural practices, soil type and environmental conditions. Factors which must be considered when developing a herbicide program for wet-seeded rice are the herbicide itself, weed flora, application technique and time, crop tolerance and cost effectiveness (Moody 1992). Chemical control in dry-seeded rice has been inconsistent from site to site and from year to year at the same site. The inconsistency could be due to varying weed species, weed populations, soil and climatic conditions. Therefore, flexibility in herbicide usage to suit conditions is critical to the acceptance of herbicides for dry-seeded rice culture (Moody 1981).

The incorporation of chemical methods in the stale-seed bed technique are more effective than cultural methods. After land preparation, planting is delayed until the first flush of weeds which emerging after rain have been controlled by herbicides. Chemical methods are superior to mechanical ones because they do not bring more weed seeds to the soil surface where conditions are more favourable for germination. Excellent weed control with butachlor has been obtained and less time was required to hand weed stale-seeded plots. Higher yields in stale-seeded bed plots have been obtained when butachlor, pendimethalin, thiobencarb plus 2,4-D were used.

When a herbicide is incorporated before planting, it is less subject to weather vicissitudes, therefore weed control is more consistent. However, pre-emergence herbicides are dependent upon moisture for activation, their application to dry-seeded rice without follow-up rain can result in complete loss of effectiveness through deactivation and volatilization (Moody and Mukhopadhyay 1982).

It is more difficult to find suitable pre-emergence herbicides for weed control in wet-seeded rice than in transplanted rice. This is because rice and grass weeds are at the same stage of development in wet-seeded rice, therefore they may show the same degree of susceptibility to the applied herbicide.

Pre-emergence herbicides that control weeds in wet-seeded rice in the Philippines include butralin, piperophos dimethametyrn and butachlor and thiobencarb. The recommended time of application of most of these compounds is 6 days after seeding (DAS). Propanil and propanil-fenoprop are post-emergence herbicides that have performed well across a range of water regimes. In Malaysia, Baki and Azmi (1992) reported that pretilachlor at 0.5 kg ai/ha applied 3-5 DAS, or mixture of molinate + 2,4-D IBE (2.5+0.03 kg ai/ha); molinate + bensulfuron (2.5+0.03 kg ai/ha); molinate + bensulfuron (2.5+0.03 kg ai/ha); thiobencarb + 2,4-D IBE (2.5+0.5 kg ai/ha); propanil + molinate (2.5+0.5 kg ai/ha) and cinosulfuron (0.04 kg ai/ha) applied at 8-10 DAS on moist or moderately inundated field conditions (5-10 cm depth), can control a broad spectrum of sedges, grasses and broadleaved weeds.

Under dry-seeded conditions, pre-emergence herbicides which are dependent on moisture for activation, fail to give adequate weed control due to delayed water supply. On the other hand, heavy downpours result in ponding of water and cause severe phytotoxicity to dry-seeded rice.

Moody (1982) reported that in the Philippines, single herbicide treatments are unsatisfactory for dry-seeded rice weed control; herbicide combinations are generally superior. A combination of thiobencarb and propanil applied early post-emergence has given good weed control in Japan. Other herbicide combinations that have given promising results are: propanil and MCPA applied sequentially post-emergence in Thailand and sequential applications of butachlor, terbutryne and piperophos - dimethametryne in Korea.

In Malaysia, fenoxaprop-p-ethyl (48-60 gm ai/ha) applied at 35 DAS with spray volumes ranging from 240-300 L/ha. was found to be effective as a late post-emergence treatment for the control of *Echinochloa crus-galli*, *Echinochloa colona* (L.) Link, *Leptochloa chinensis* and *Ischaemum rugosum* Salisb. in dry-seeded rice. Fenoxaprop-p-ethyl has the widest application window among the currently known herbicides for grassy weed-control in rice. It is effective up to the tillering stage of grassy weed growth. It is equally effective in both dry and inundated conditions. Its efficacy is not affected by rainfall at 1-4 hours after application.

INTEGRATED WEED MANAGEMENT

Weed rice ecological relationships are never static. The continuous adaption of any particular rice production practice causes a shift in dominance and distribution of rice weeds. In the formulation of weed management programs, the type of rice culture, cultivars grown, tillage, crop establishment methods, planting density, fertilizer application and water management need to be systematically manipulated, so as to create situations favourable for crop growth, but unfavourable for weed survival. Systematic approaches should be adopted in the formulation of integrated management strategies.

In the Muda Irrigation Scheme of Malaysia, the widespread and expanding practice of the direct seeding technique since 1980 has resulted in dramatic changes in the weed spectrum. Grassy weeds which are suppressed in the transplanted fields, emerge as dominant weed species in the direct seeded fields.

In the off season of 1987, when more than 90% of the Muda area was direct-seeded, *Echinochloa* spp. and *Leptochloa chinensis* infestation in combination caused severe yield losses (30-100%) in 10,781 ha or 11.2% of the total rice fields (96,000 ha). Realising that no single weed control method is best for use under all circumstances, the Muda Agricultural Development Authority (MADA) decided to adopt the integrated weed management (IWM) approach to mitigate the grassy weed problems in 1988. IWM in rice emphasizes the simultaneous combination of various methods, and takes into consideration the need to sustain land, water, crop and human resources.

The current approach adopted by MADA in the implementation of IWM in rice is as follows:

- * Monitoring weed-rice interaction in the agro-ecosystem.
- * Understanding the farmers' perception of weed problems and control.
- * Developing simplified technology for IWM.
- * Conducting multi-media strategic extension campaign on IWM.

The IWM technology for wet-seeded rice emphatically stresses the following practices:

- * Adopting dry rotovation in the early first season (February and March) to conserve the soil bearing capacity and soil moisture.
- * Carrying out raking or levelling upon arrival of water to ensure uniform seedling establishment.

- * Avoiding an excessively high seeding rate (more than 100 kg/ha) to minimise pest and disease infestations.
- * Using weed-free, clean seeds.
- * Constructing field ditches to facilitate irrigation and drainage.
- * Filling vacant spots in the fields as early as possible with healthy seedlings.
- * Applying pre-emergence herbicides on wet-seeded at the right time with proper spray volume under suitable water conditions; avoiding the use of the same herbicides every season.
- * Applying 40 kg N: 30 kg P_2O_4 :20 kg K_2O at 15 to 20 days after seeding (DAS), followed by 30 kg N at 45 to 55 DAS, and another 30 kg N at 75-80 DAS.
- * Fertilizer should be applied after weed control.
- * Avoiding insecticide application within the first 30 days after seeding for leaf-folder control.
- * Carrying out hand weeding regularly.
- * Adhering closely to the irrigation schedule.
- * Visiting rice fields regularly for crop inspection.

FUTURE NEEDS IN RESEARCH AND TECHNOLOGY DEVELOPMENT

Biological Characteristics of Weeds

A deeper understanding of the biological characteristics of weed species is important to establish a reasonable weed control technology. Understanding the phenomenon of allelopathy is important and can lead to deeper insights into crop interference mechanisms due to weeds. It offers the possibility of beneficial use of special substances contained in plants for future biotechnological development.

Yield Loss Assessment

Forecasting yield loss due to weed competition includes determining the cost and profitability of weed control and the extent to which weed control is necessary. As yield loss by weed competition involves many factors such as varieties, spacing, crop vigour, population density, timing of crop emergence, soil fertility, climate and duration of competition, a quantitative approach to research on yield loss caused by weed competition can be helpful to integrate weed control practices (Chisaka 1977). Development of better simulation models will definitely lead to deeper insights on rice-weed competition to minimize crop losses.

Biological Weed Control

Biological weed control is now technically feasible. However, only a few have been developed to the level of field use, e.g. *Colletotrichum gloeosporioides* f. sp. *aeschynomene* for control of *Aeschynomene virginica* (L.) B.S.P. in rice; tadpole shrimp (*Triopus longicaudatus*) for the control of weeds in transplanted rice in Japan; weevil *Cyrtobagous salviniae* Calder & Sands for control of *Salvinia molesta* D.S. Mitchell in Australia, Papua New Guinea, and India and weed suppression in transplanted rice with *Azolla pinnata* R. Br. (Janiya and Moody 1981). Development of this technique requires a multi-disciplinary approach to provide essential technical guidelines for research and technology development.

Farmers' Perception

The best weed control is achieved through the integration of several weed control methods applied simultaneously (Moody and De Datta 1982). However, adopting integrated weed management (IWM) is dependent on farmers' understanding of weeds, familiarity with the technique, experiences and resources. Therefore, farmers' knowledge, attitude and practices in

making management decisions must be investigated further.

Herbicide Development

Future research should be focused on various herbicide combinations to achieve optimum weed control with least phytotoxicity to rice. Suitable herbicide combinations with wider application windows, under various moisture regimes and soil conditions, will be more flexible in application timing. These will help in controlling a wider weed spectrum. Use of various adjuvants to enhance herbicide efficacy at low costs is another important aspect that requires further research attention.

As labour costs are escalating in many rice producing countries, shifting from more labour-intensive to less labour-intensive weed control techniques is becoming popular. Herbicide application methods with shaker bottles, control droplet application, or direct application of undiluted herbicides to rice fields offer labour saving advantages. Hence, studies on safeners to minimize phytotoxicity is another important aspect for weed scientists. The impact of herbicides on rice soils, as well as other flora and fauna, should also be further investigated. Research on the dissipation and degradation of herbicides in relation to temperature, photo-decomposition, and microbial degradation are essential (Chen 1981). Regional and international collaborative research programs on herbicide problems should be strengthened.

Last but not least, the creation of awareness among farmers on proper herbicide management will surely reduce the adverse impact of herbicides on the rice agro-ecosystem.

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CHAPTER 8

WEED MANAGEMENT IN DEEPWATER RICE

WEED MANAGEMENT IN DEEPWATER RICE

Prasan Vongsaroj

INTRODUCTION

Weeds are a major problem limiting the growth and yield of deepwater rice. The land is generally dry at seeding, becomes moist with rain and is finally flooded. The various land conditions from upland to lowland and to flooded are suited to all types of weeds, including upland, lowland and aquatic weed types. Infestation levels tend to be higher than for other types of rice cultivation. One single method of weed control is not enough hence the integration of weed control methods and weed management is needed. Smith and Reynolds (1966) defined weed management as a system that uses all suitable methods in a compatible manner to reduce weed populations and maintain them at a level below that causing economic injury. Plucknett *et al.* (1977) explained that weed management is a part of total vegetation management; namely the use of various combinations of cultural, manual, mechanical, chemical, biological and ecological methods in an attempt to create an environment that is detrimental to weeds and favourable to crops. Weed management must conform to the needs of farmers; which means being simple (easy to use), effective (reduces weeds and increases crop yield), efficient (involves minimum effort and time), robust (produces consistent results over time), flexible (adaptable to the entire farm) and motivating (feels good to use it; without risk) (Kon 1993). Prior to achievement of weed management, knowledge of the weeds in deepwater rice and methods of control are needed as basic information, as well as understanding of their ecosystem.

DEEPWATER RICE

Deepwater is mostly direct seeded under dry conditions for 1-3 months when it rains the land becomes moist and floods with maximum depths from 50 cm to 400 cm. In some areas, the dry period is short because of the early start of rainy season. Yields in Thailand average around 2.0 t/ha. The luxuriant growth of foliage is partly nourished by silt and nutrients in flood water. Farmers seldom apply fertiliser (Catling 1992). Farmers generally broadcast dry seeds, but transplanting with tall seedlings is done. Deepwater rice is grown in many countries namely India, Bangladesh, Thailand, Vietnam, Myanmar, Mali, Cambodia, Sri Lanka, Niger, Nigeria, Senegal, Gambia, Sierra Leone, Guinea and Mauritania (Vergara 1985; Catling 1992).

WEEDS

Weeds in deepwater rice are classified as either grass (G), broadleaf (B), sedge (S), fern (F), and algae (A) (Table 1). They can be grouped by their habitat before and after flooding (DeDatta 1981). After rice seeds are sown under dry conditions, grasses such as *Oryza rufipogon* Griff., *Echinochloa colona* (L.) Link, *Ischaemum rugosum* Salisb., *Cynodon dactylon* (L.) Pers., *Urochloa reptans* (L.) Stapf are the most abundant. Sedges found in the period included *Cyperus rotundus* L., *Eleocharis dulcis* (Burm. f.) Henschel and *Fimbristylis miliacea* (L.) M. Vahl. Common broadleaved weeds are *Pentapetes melochia*, *Aeshynomene indica* L., *Cyanotis axillaris* (Blume) Sweet, *Sesbania sesban* L. Merr. and *Ipomoea aquatica* Forsskal. When the land becomes wet, weeds such as *Marsilea crenata* C. Presl, *Chara zeylanica* Willd., *Nymphaea nouchalii* Burmanf. appear (Table 1). The weeds either complete their growth cycle before flooded conditions, such as *Echinochloa colona*, *Cynodon dactylon* or are killed by rising water (Catling *et al.* 1987). Tall grass like *Echinochloa stagnina* (Retz.) P. Beauv., *Leersia hexandra* Sw., *Ischaemum rugosum*, *Ischaemum barbatum* Retz., *Oryza rufipogon* and *Cyanotis axillaris* elongate their stems to survive as emergent plants. Broadleaved weeds like *Melochia*

Table 1. Weeds in deepwater rice (Adapted from Varshney and Singh 1976; Nantasomsaran *et al.* 1988b; Saw Ler Wah 1994; and others)

Weed species	Type of weeds	Country	Time of infestation
<i>Echinochloa colona</i> (L.) Link	G	Ba,Th	BF
<i>Echinochloa crus-galli</i> (L.) P.Beauv.	G	Ba,Th	BF
<i>Echinochloa stagnina</i> (Retz.) P.Beauv.	G	Th	AF
<i>Echinochloa picta</i> (Koen.)Michael	G	Th	AF
<i>Echinochloa lelievrei</i> (Chevel.)Berhurt	G	Mal	BF,AF
<i>Ischaemum rugosum</i> Salisb.	G	Ba,Th	BF,AF
<i>Ischaemum barbatum</i> Retz.	G	Th	BF,AF
<i>Oryza rufipogon</i> Griff.	G	Th	BF,AF
<i>Oryza barthii</i> A. Chev.	G	Mal	BF,AF
<i>Oryza glaberrima</i> Steud	G	Mal	BF,AF
<i>Oryza longistaminata</i> Chev. et Roehr.	G	Mal	BF,AF
<i>Oryza stapffii</i> Roshev.	G	Mal	BF,AF
<i>Oryza sativa</i> var. <i>fatua</i> Prain	G	Ba	BF,AF
<i>Setaria geniculata</i> (Lam.) P.Beauv.	G	Th	BF,AF
<i>Paspalum cambogiense</i> Balansa	G	Th	BF,AF
<i>Leersia hexandra</i> Sw.	G	Th	BF,AF
<i>Hymenachne pseudointerrupta</i> Muell	G	Ba,Th	BF,AF
<i>Leptochloa chinensis</i> (L.) Nees	G	Th	BF,AF
<i>Panicum repens</i> L.	G	Th	BF
<i>Hygroryza aristata</i> (Retz.) Nees ex Wright & Arn.	G	Ba	BF,AF
<i>Vossia cuspidata</i> (Roxb.) Griff	G	Ba	BF,AF
<i>Eleusine indica</i> (L.) Gaertn.	G	Ba	BF
<i>Brachiaria</i> sp.	G	Mal	BF
<i>Paspalum scrobiculatum</i> L.	G	Mal	BF,AF
<i>Sacciolepis cymbiandra</i> Stapf.	G	Mal	BF
<i>Chamaeraphis gracilis</i> Hack	G	Ba	BF
<i>Aeschynomene sensitiva</i> Sw.	B		BF,AF
<i>Aeschynomene indica</i> L.	B		BF,AF
<i>Sesbania sesban</i> (L.) Merr.	B	Mal	BF,AF
<i>Achyranthes aspera</i> L.	B	Mal	BF
<i>Alternanthera sessilis</i> (L.) R.Br. ex Roem. & Schult.	B	Mal	BF,AF
<i>Melochia corchorifolia</i> L.	B	Mal,Th	BF
<i>Corchorus fascicularis</i> Lam.	B	Mal	BF
<i>Ipomoea aquatica</i> Forssk.	B	Ba,Mal,Th	BF,AF
<i>Ipomoea gracilis</i> R.Br.	B	Th	BF
<i>Neptunia oleracea</i> Lour.	B	Mal	AF
<i>Nymphaea lotus</i> L.	B	Mal	AF
<i>Nymphaea nouchali</i> Burm.f.	B	Th	AF
<i>Nymphoides indica</i> (L.) O.K.	B	Mal,Th	AF
<i>Cyperonina</i> sp.	B	Mal	AF
<i>Utricularia stellaris</i> L.f.	B	Mal	AF

Table 1. Cont.

Weed species	Type of weeds	Country	Time of infestation
<i>Utricularia aurea</i> Lour.	B	Th	AF
<i>Borreria filifolia</i> (S & Th.) K. Schum	B	Mal	BF
<i>Polygonum mildbredii</i>	B	Mal	AF
<i>Eichhornia crassipes</i> (Mart.) Solms	B	I, Ba	AF
<i>Nymphaea stellata</i> Willd.	B	I	AF
<i>Nelumbo nucifera</i> Gaertn.	B	I, Th	AF
<i>Hydrilla verticillata</i> (L.f.) Royle	B	I	AF
<i>Limnophila heterophylla</i> Benth.	B	Th	AF
<i>Typha</i> sp.	B	I, Th	AF
<i>Lemna</i> sp.	B	I, Th	AF
<i>Vallisneria</i> sp.	B	I	AF
<i>Mariophyllum</i> sp.	B	Th	AF
<i>Potamogeton</i> sp.	B	I	AF
<i>Pistia stratiotes</i> L.	B	I, Th, Ba, My	AF
<i>Heliotropium bracteatum</i> R.Br.	B	Th	BF
<i>Sesbania aculeata</i> Poir.	B	Ba	BF, AF
<i>Sesbania paludosa</i> Jacq.	B	Ba	BF, AF
<i>Monochoria vaginalis</i> (Burm.f.) Presl	B	Ba, Th	AF
<i>Ottelia alismoides</i> (L.) Vahl	B	Th	AF
<i>Najas graminea</i> Del.	B	Th	AF
<i>Ceratophyllum demersum</i> L.	B	Th	AF
<i>Alisma plantago-aquatica</i> L.		My	AF
<i>Alternanthera philoxeroides</i> (Mart.) Griseb.	B	My, Th	AF
<i>Cyanotis axillaris</i> (L.) D.Don	B	My, Th	BF, AF
<i>Pentapetes phoenicia</i> L.	B	My, Th	BF, AF
<i>Cyperus rotundus</i> L.	S	I, Ba, Th	BF
<i>Cyperus iria</i> L.	S	I, Ba, Th	BF
<i>Cyperus difformis</i> L.	S	I, Ba, Th	BF, AF
<i>Eleocharis dulcis</i> (Burm.f.) Trin. ex Henschel	S	I, Ba, Th	BF, AF
<i>Eleocharis plantaginea</i> (Retz.) Roem.	S	Mal	BF, AF
<i>Scirpus praelongatus</i> Poir	S	Mal	BF, AF
<i>Pycreus</i> sp.	S	Mal	AF
<i>Fimbristylis littoralis</i> Gaud	S	Th	BF
<i>Fimbristylis racilentia</i> Hanoe	S	Th	BF
<i>Cyperus pulcherrimus</i> Willd. ex Kunth	S	Th	BF
<i>Salvinia</i> sp.	F	I, Th	AF
<i>Chara zeylanica</i> Willd.	A	I, Th	AF

I=India, Ba=Bangladesh, Mal=Malaysia, Th=Thailand, My=Myanmar, G=Grass, B=Broadleaf, S=Sedges, F=Fern, A=Algae, BF=Before flooding and AF=After flooding.

corchorifolia L., *Pentapetes phoenicea* L., *Sesbania sesban*, *Monochoria vaginalis* (Burman f.) Kunth and *Scirpus grossus* L.f. are adapted to rising water while *Ipomoea aquatica* a root creeping vine, sends out runners along the water surface and either produces seeds or under favourable conditions is perennial. Flooded fields are colonised by a complex of free floating

plants, emergents and submerged aquatic plants. Some weeds that are adapted to pH 4 and below include *Scirpus grossus*, *Eleocharis dulcis*, *Phragmites karka* (Retz.) Trin. ex Steud. and *Cyperus iria* L. (Grabial *et al.* 1986). Wild rice is the most difficult weed in deepwater rice causing a big yield losses. *Ischaemum rugosum* caused yield reductions to 92% when the population was 2 plants/m² and 37% with 64 plants/m² (Supatanakul *et al.* 1985). In Thailand, for 7 provinces where deepwater rice is grown, it was found that 282 of 307 farmers had weed problems (Niyomvit 1984).

METHODS OF WEED CONTROL

Prevention

Weed damage can be reduced by using purified seeds - free from weed seeds, especially *Oryza rufipogon*. Wild rice normally has a similar size and shape seed to cultivated rice but sheds seed. To use new seed from a place where there is no wild rice should help minimise wild rice problems (Vongsaroj 1976). A high percentage germination as well as a high seedling vigour is of advantage for competition with weeds. Another method of prevention is to have a longer period of fallow after harvesting rice (Vongsaroj 1976).

Cultural Methods

Land preparation. Land preparation is the first step in growing rice. In the past, ploughing was practised by animal drawn ploughs and was done while the soil was wet, after the majority of weeds had germinated. Weed seedlings were killed by turning over into the soil. Now tractors are available, and ploughing can be done under dry conditions. Weed seeds on the soil surface are buried into the soil, while the previous season's seeds are brought the up to surface for germination and cause severe infestation (Vongsaroj 1976). Increasing the number of ploughings can minimise weed problems, by ploughing at 2 weeks after heavy rain, letting new weed seedlings emerge, then harrowing when new weed seedlings come up, broadcast rice seeds and harrowing (Vongsaroj 1976). It was found in Myanmar (Table 2) that two ploughings and one ploughing plus harrowing as well as straw burning minimised wild rice populations (Saw Ler Wah 1993). Puckridge *et al.* (1988) found that delayed tillage in 1986 reduced the number of wild rice plants by 50 % but the number remaining still averaged more than 100/m². The yield of rice for the third sowing was 7 times that of check. Puckridge *et al.* (1988) also found that sowing rice seeds on puddled soil gave the lowest rice yields of 1.4-16 t/ha. Yingviwatanapong (1986) found that one plough with 3 discs at 3.0-12.5 cm depth reduced the *Eleocharis dulcis* by 49%. In the case of a heavy infestation of a specific weed where other methods are not effective, burning straw after harvest was proved to reduce wild rice populations (Vongsaroj 1976).

Method of planting. Deepwater rice is generally grown by direct seeding. The weeds and crop germinate at the same time and infestation of weeds is very severe. In some areas where the rain starts very early, the dry period is too short for broadcast sowing of rice. When farmers broadcast pre-germinated rice seeds, fewer grass weeds can germinate, broadleaf weeds and sedges need some time for germination, so weeds tend to be too small to compete with rice. In Myanmar, transplanting of tall seedlings is popular to overcome wild rice problems (Vongsaroj 1992).

Rice cultivar. There are many rice cultivars in deepwater rice, each variety has a different ability to compete with weeds. India is going to release a new deepwater rice variety which has branching stems and a large leaf canopy to compete with weeds (Thakur, personal communication 1993).

Table 2. Various methods of wild rice control in deepwater rice at Wakema, Myanmar (Saw Ler Wah, 1993).

Treatments	Dry wt. of wild rice	Yield of rice (t/ha)
Two ploughings + harrowing	0a	2.37a
One ploughing + harrowing	0a	2.11a
Straw burning	0a	2.24a
Paraquat	0a	1.68a
Glyphosate	0a	2.43a
NA + oxadiazon	3.63a	2.09a
Untreated check	51.0b	1.35a
Hand weeding	0a	22.3a

Value followed by the same letters are not significantly different at 5 % level by Duncans Multiple Range Test.

Rice plant density. Weeds affect rice growth mostly at the seedling stage when stand density of rice is established. A good stand can minimise weed problems. Farmers generally use a very high seed rate at 156 kg/ha in Thailand. Sowing of rice seed at increasing rates 62, 156 and 281 kg/ha, reduced dry weight of weeds, namely *Eleocharis dulcis*, *Aeschynomene aspera* L., *Ipomoea aquatica*, *Pentapetes phoenicea*, *Melochia corchorifolia* and *Cyanotis axillaris* (Supatanakul *et al.* 1985) and *Ischaemum rugosum*. The same trend was found by Yingviwatanapong (1986) with *Eleocharis*, the higher seed rate of rice, the smaller the population of *Eleocharis* was obtained. High seed rate minimises weed population but yield will decline, if the seed rate is too high. Supatanakul *et al.* (1985) found that even though dry weight of weeds declined, the yield of rice was lower when the seed rates were over 218 kg/ha (Table 3).

Table 3. Effect of seed rate on weed and rice yield at Prachin Buri, Thailand (Supatanakul and Khomvilai, 1985)

Seed rate (kg/ha)	Dry weight of weeds (g/m ²)	Yield of rice (kg/ha)
62.5	27.01	731.25
93.25	17.59	1212.5
125.0	21.51	1205.63
156.25	16.15	1228.13
187.5	16.87	1108.75
218.25	12.72	1405.0
250.0	13.11	1259.30
281.25	7.53	1223.13

* Weeds are: *Ischaemum rugosum* Salisb., *Eleocharis dulcis* (Burm.f.) Henschel, *Aeschynomene aspera* L., *Ipomoea aquatica* Forssk., *Pentapetes phoenicea* L., *Melochia corchorifolia* L. and *Cyanotis axillaris* Roem & Schult.

Time of planting. Delayed seeding after a heavy rain and a dry period will reduce the weed problem. Delaying seeding of rice from May to June, reduced wild rice population (Puckridge *et al.* 1988). Vongsaroj *et al.* (1973) studied germination of weed seeds namely *Aeschynomene aspera*, *Melochia corchorifolia*, *Eclipta prostrata* (L.)L., *Jussiaea linifolia* Vahl, *Pentapetes phoenicea*, *Sesbania javanica* Miq., *Echinochloa colona* and *Leptochloa chinensis* (Roth) Nees under room temperature and found that most of the weeds germinated early in the wet season.

Cropping system. Monoculture of rice leads to an increase in weed populations especially well adapted to rice growing conditions. In deepwater rice in Thailand, a field crop can be grown before or at the same time with rice. Some farmers grow sweet potato, sweet corn, mungbean, sesame, sorghum and soybean before rice. In experiments by Vongsaroj *et al.* (1993) sesame and mungbean were grown in rows at the same time as rice and 20 days prior to rice seeding. The herbicides oxadiazon and fenoxaprop-p-ethyl were used and it was found that oxadiazon could be used safely to all plants. It was found that *Ipomoea aquatica* had lower density and dry weight in a treatment in which rice was grown 20 days after sesame and mungbean (Table 4). Growing rice with sesame, mungbean had less dry weight of *Cyanotis axillaris* and *Ipomoea aquatica* than growing only sesame and mungbean (Table 4).

Table 4. Number of weeds at 45 days after seeding of field crops (Vongsaroj *et al.* 1991).

Treatment ^a	Number of weeds ^b /0.5 m ²					Dry weight of weeds ^b /0.5 m ²				
	1	2	3	4	5	1	2	3	4	5
S+M	4.5 a	7.8 ab	1.5 a	16.5 a	2.0a	3.7 a	7.1 a	0.3 a	18.8 a	2.0 b
S+M+R (0 DASf)	5.0 a	20.3 a	1.3ab	10.3 ab	1.8 a	3.5 a	4.1 abc	0.3 a	9.2 bc	4.9 a
S+M+R (20 DASf)	3.8 a	7.3 b	1.5 a	10.0 abc	1.8 a	3.3 a	2.6 bc	0.3 a	15.3 ab	1.5 b
S+M+oxa.	0 b	6.8 ab	0.3 a	6.3 bcd	0 c	1.6 a	2.3 c	0.1 a	3.1 cd	0 b
S+M+R (0 DASf) +oxa.	0 b	3.3 b	0.8 a	5.0 bcd	0 c	2.8 a	1.3 c	0.2 a	1.6 d	0 b
S+M+R (20 DASf)+oxa.	0 b	4.5 b	0.8 a	3.8 bcd	0.5	0.4 b	1.6 c	0.1 a	2.7 cd	0.7 b
S+M+fenoxaprop.	0.5 b	14.0 ab	1.3 a	10.8 ab	0.5	0.9 b	3.8 abc	0.9 a	14.1 ab	0.2 b
S+M+R (0 DASf)+ fenoxaprop.	1.0 b	21.0 a	1.3 a	7.3 bcd	1.3	0.7 b	6.4 ab	0.5 a	5.9 cd	1.4 b
S+M+R (20 DASf) + fenoxaprop.	0 b	17.5 ab	1.0 a	5.0 bcd	1.8 a	0.8 b	3.6 abc	0.3 a	7.0 cd	1.3 b
S+M+HW	1.25 b	5.2 ab	1.0 a	2.8 d	0.5	0.7 b	1.0 c	0.4 a	1.9 d	0.2 b
S+M+R (0 DASf) +HW	1.56 b	3.5 a	2.0 a	3.0 d	0.5	0.6 b	0.8 c	0.8 a	2.5 cd	0.7 b
S+M+R (20 DASf) +HW	1.50 b	5.0 ab	2.3 a	3.3 cd	0.5	0.6 b	1.3 c	0.4 a	2.3 cd	0.7 b

^a S=sesame, M=mungbean, R=rice, and DASf=days after sesame and mungbean sowing.

^b 1. *Leptochloa chinensis* (L.) Nees

2. *Cyanotis axillaris* (L.) D. Don

3. *Euphorbia hirta* L.

4. *Ipomoea aquatica* Forssk.

5. *Ipomoea gracilis* R.Br.

Manual Weeding

As the yield of deepwater rice is quite low, few farmers in Thailand hand weed. Catling (1992) and Niyomwit (1984) found that farmers in Thailand controlled weeds by the methods of chemical, hand weeding and both at 74%, 3% and 5% respectively. For hand weeding, the time of weeding is important. It should coincide with the critical period of weed competition. Nantasomsaran *et al.* (1988a) studied competition of *Echinochloa colona* with deepwater rice and found that the critical period of this weed was 4 weeks after emergence of rice. In Myanmar, farmers cut both rice and weeds in the area where wild rice is a big problem, because cultivated rice can elongate stems more rapidly than wild rice (Saw Ler Wah, personal communication, 1992). In Thailand, Kupkanchanakul *et al.* (1992) found that rice can be cut for herbage, and this could reduce weed populations as well.

Biological Control

In deepwater rice, *Pistia stratiotes* L. is one common weed which can be controlled by an insect, namely *Epipsammia pectinicornis*, introduced from U.S.A. in 1976 (Napompeth 1992).

Chemical Control

Herbicides in deepwater rice can be applied as pre- and post-emergence. The pre-emergence herbicides like oxadiazon, butachlor-ioxynil-2,4-D, butachlor, bifenox, thiobencarb and oxyfluorfen sprayed after seeding give good weed control especially on *Echinochloa colona* (Table 5). Molinate-propanil, thiobencarb-propanil, ioxynil-2,4-D-propanil, bifenox-propanil, propanil-2,4-D, ioxynil + 2,4-D, propanil, bromoxynil-MCPA and butachlor-propanil gave good weed control applied post-emergence (Table 6). 2,4-D is the most popular herbicide in Thailand and can control broadleaf weeds and sedges effectively (Vongsaroj and Chinawong 1982). An antidote, NA (1,8-naphthalic anhydride), is used to increase selectivity between wild rice and rice when high rate of herbicides is applied (Parker and Dean 1976). Supatanakul and Vongsaroj (1976) found that amiben and alachlor were safe to rice when mixed rice seeds were treated with NA at 0.01% by weight and the wild rice population was reduced. Butachlor and molinate, recommended rice herbicides, minimised wild rice populations and did not harm rice when sprayed with antidote even at high rates of application.

Table 5. Effect of pre-emergence herbicides on density of *Echinochloa colona* and yield of DWR in a farmer's field. Phu Khao Tong, Ayutthaya Province, Thailand, 1983 WS. (Vongsaroj *et al.* 1988).

Treatment ^a	Application rate (kg ai/ha)	<i>E. colona</i> plants ^b (no./m ²)	Yield (t/ha)
Oxadiazon	1.0	48 a	2.0
Butachlor + Ioxynil - 2,4-D	0.75 + 0.07 - 0.43	60 a	1.7
Butachlor + 2,4-D	0.75 + 0.5	62 a	1.7
Butachlor	2.0	68 ab	1.8
Bifenox	2.0	74 abc	2.0
Thiobencarb	3.0	91 bc	2.4
Oxyfluorfen	0.5	100 c	1.8
Untreated check	-	169 d	1.9

^a(+)=tank mix. ^bCounts at 70 d after application of herbicide.

Table 6. Effect of post-emergence herbicides on density of *Echinochloa colona* and yield of DWR in a farmer's field. Phu Khao Tong, Ayutthaya, Thailand, 1983 WS. (Vongsaroj *et al.* 1988).

Treatment ^a	Application rate (kg ai/ha)	Weed control ^b	E. colona ^c (no./m ²)	Yield (t/ha)
Molinate-propanil	1.0 + 1.0	5	47 a	1.0
Thiobencarb-propanil	1.3 + 1.7	3	47 a	1.1
Ioxynil-2,4-D-propanil	1.0	4	53 ab	1.2
Bifenox + propanil	1.5 + 1.5	6	53 ab	1.1
Oxadiazon + propanil	0.8 + 1.5	6	54 abc	1.1
Propanil-2,4-D	1.67 - 0.33	7	67 abc	1.3
Ioxynil-2,4-D	0.14 - 0.86	1	67 abc	1.4
Propanil	2.0	2	77 bc	1.0
Bromoxynil + MCPA	1.0 + 1.0	3	85 c	1.1
Butachlor + propanil	0.8 + 1.5	4	88 c	1.3
2,4-D	0.75	0	206 d	1.3
Untreated check	-	0	191 d	0.8

^a (-)=proprietary mixture, (+)=tank mix,

^b Visual rating, 23 d after herbicide application, on a scale of 0-10: 0=no control, 10=complete control.

^c Counts at 62 d after application. Mean of 4 replications.

CONCLUSION

The weeds in deepwater rice are dynamic, changing with land conditions which are entirely dependent on rainfall. If there is enough dry period after heavy rain, the degree of successful weed control from one or more ploughings or harrowings is very high. Weed-free rice seed is effective for the reduction of wild rice infestation especially with antidote. Cropping systems in deepwater rice will take some time to be proven as a effective weed control methods but they result in soil improvement and income from other legume crops maximising the use of farm labour. As rice yields are low, weed control needs to be inexpensive. Manual weeding now is becoming more difficult because it is expensive and there is a shortage of labour. Chemical weed control is effective but costly. Not all farmers can afford this method. Biological control is a new approach for weed control, but only one weed, *Pistia stratiotes*, can be controlled hence further research is urgently needed.

Weed management in deepwater rice need not comprise all methods of weed control. The most practical and suitable methods for individual farmers are required to minimise weed problems.

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CHAPTER 9

PRESENT STATUS AND PROBLEMS OF WEED MANAGEMENT IN RICE IN SOUTH ASIA

PRESENT STATUS AND PROBLEMS OF WEED MANAGEMENT IN RICE IN SOUTH ASIA

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INTRODUCTION

People living in the Asian continent account for 53 % of world's 6.5 billion population. Around the time when Asia was being sadly written off, the process of green revolution was quietly beginning. With faster economic growth, East Asia has become largely a middle class continent but South Asia's population is so huge, that it will continue to put increasing pressure on the already strained food producing resources. Rice is the major food crop grown in South Asia comprising countries India, Bangladesh, Pakistan, Nepal and Sri Lanka. The crop is grown under different ecological and hydrological situations and subjected to severe abiotic and biotic stresses and hence yields are low. So far, increased rice production per unit area but not increased rice area has kept up with demand. The yield increase is mainly due to high yielding varieties, fertiliser, cultural techniques and irrigation practices. Intensification has brought weeds to the forefront. With the advent of new technologies and diversities in rice cultures, improved weed control methods have been introduced and traditional methods have been improved upon, but none have been abandoned, altogether. In South Asia, farmers choose the combination of weed control inputs that provide the desired degree of weed control at lowest cost. The relative cost of a particular input combination calls for an integrated approach to minimise weed control costs in different rice cultures.

LAND USE PATTERN

Land utilisation for rice culture is different in various South Asian countries. Irrigated rice culture as a percentage of total rice area is 100, 77, 44, 23 and 16 in Pakistan, Sri Lanka, India, Nepal and Bangladesh, respectively. Average yields of these countries vary from 2.44 t/ha to 2.99 t/ha compared with 3.63 t/ha in the whole of Asia. Rice culture in these countries is characterised by different ecosystems - rain-fed, upland and lowland of different submergence levels and irrigated land (Table 1).

Table 1. Rice area (x1000 ha), average yield (t/ha) and distribution of rice crop area (%) by production environment in South Asia.

Country	Area	Yield	Rice crop area by production environment			
			Irrigated	Rain-fed	Upland	Deepwater
India	41800	2.62	44	35	15	6
Bangladesh	10600	2.77	19	49	8	24
Nepal	1433	2.44	23	66	3	8
Pakistan	2127	2.47	100	-	-	-
Sri Lanka	735	2.99	77	15	1	7

Source: *World Rice Statistics, 1990*, IRRI, 1991.

Irrigated transplanted rice is more common in north-west India, south India and Pakistan, while irrigated direct sown or broadcast rice culture is more common in Sri Lanka.

Rain-fed lowland rice is common in dry and intermediate zones of Sri Lanka, Bangladesh, parts of India and Nepal. The one field system in which rice is grown more than once in a year in the same field is quite common in many parts of South Asia. The two field system in which wheat is continuously rotated with rice is prevalent in North-West India and Pakistan. Details of different rice cultures based on planting time are given in Table 2.

Table 2. Different types of rice cultures based on planting time in South Asia.

Country	Planting time		
	March onwards	May onwards	October to February
Bangladesh	Upland direct seeded, broadcast deep water rice and transplanted rice	Transplanted	-
India			
North-west India	-	Transplanted and direct sown	-
South India	Direct seeded and transplanted	Direct seeded and transplanted	Direct seeded and transplanted
Central India	-	Transplanted, direct seeded and broadcast	-
North-east India	Direct seeded and broadcast deep water rice	Transplanted and direct seeded	Direct seeded irrigated
Pakistan	-	Transplanted	-
Nepal	Transplanted irrigated	Direct seeded irrigated and rainfed	-
Sri Lanka	Direct seeded and transplanted	Transplanted	Direct seeded and transplanted

These diverse topographical and hydrological situations influence the microclimate of the crops and alter both intensity and diversity of weeds. The cultural systems in different crop sequences traditionally followed in these countries including direct seeding and transplanting in different land types influence the competitive behaviour of weeds and the rice crops. In Bangladesh, a short dry seeded rice is grown before the monsoon because normal transplanting is not possible without irrigation water (Ahmed *et al.* 1993). In Punjab of India, 40 plus irrigations are given to rice grown on loam and loamy sand soils to maintain continuous submergence.

Rice is usually not substituted by other crops in the monsoon season, except for sugarcane in Western Uttar Pradesh, India. Sugarcane is an important crop in the rice-wheat rotation in parts of UP, India. It usually consists of 1 or 2 ratoons of sugarcane before returning to rice-wheat (Hobbs *et al.* 1991). The choice of the crop following sugarcane depends on the date of harvest of sugarcane. In lowlands of eastern India and Bangladesh, rice is grown after jute in the monsoon season.

Triple cropping is another pattern in the rice -wheat system. In Bangladesh, rice-wheat is practised in areas that allow the extra rice to be grown. Triple patterns with two rice crops are found in warmer areas where irrigation is available. Other non-rice crops are found in triple rice-wheat systems. Planting of a short season oilseed (*Brassica*), potato or other vegetables is common on the higher terraced, lighter soils where short duration rice varieties are used (Ahmed *et al.* 1983; Hobbs *et al.* 1991).

Many scientists encourage farmers to grow a green-manure (*Sesbania*) or short season grain legume, mungbean or cowpea in the free time between wheat harvest and rice planting but few farmers have adopted this practice so far. There is some correlation between the position in the topography and soil texture. The heavier soils tend to be in the lower terraces and depressions and light soils in the higher terraces and ridges. This influences rice yield via moisture availability, time of field preparation and planting of crop. Moreover a diverse weed flora in heavy and light textured soil arises.

WEED FLORA

In rain-fed uplands, which are uppermost in toposequence, the rice crop is direct seeded in dry condition. Aerobic soil environment and optimum temperatures in rain-fed uplands in the wet season encourages emergence and growth of annual grasses followed by sedges and dicots. Early emergence of a diverse weed flora is likely to crowd out rice plants in direct seeded rice culture, both under upland and lowland situations. In transplanted rice, the total number of weeds infesting the crop are less with the dominance of sedges in Eastern India and grasses in North-West India (Table 3).

The ten most important weeds in south Asia based on the work of different workers (Sankaran and De Datta 1985; Zafar 1988; Moody 1989; Mukhopadhyay 1991; Singh *et al.* 1992; Malik *et al.* 1992; Muthukrishnan and Purushotaman 1992), include *Echinochloa crus-galli* (L.) P. Beauv., *Cynodon dactylon* (L.) Pers., *Digitaria* sp., *Cyperus* sp., *Fimbristylis miliacea* (L.) Vahl, *Eclipta alba* (L.) Hassk., *Sagittaria* sp., *Scirpus* sp., *Monochoria vaginalis* (Burm.f.) Presl and *Mursilea quadrifolia* L.. The weed spectra in different rice cultures (Table 3) show that for an effective weed management schedule, knowledge of the weed flora is important in planning weed management research. Appreciation of the more diverse weed flora in direct seeded dryland and lowland rice compared with transplanted rice indicates how efficient weed management has to be in such systems. In direct seeded rice, weeds emerge very early, often in the first month of crop sowing. That means the whole spectrum of weed flora needs to be treated early to avoid competition. In direct seeded dry sown or broadcast rice even if weeds are controlled by manual weeding, the crop tends to suffer one or two more flushes of weeds before it enters the grand growth phase. Different flushes would also comprise various weed species which may not respond to a single herbicide. The causes of a more diversified weed flora in direct seeded rice are easy to identify including 1) more time required for early canopy cover

Table 3. Weed flora of transplanted rice, direct seeded dry sown and lowland rice of South Asia

Transplanted rice	Direct seeded	Lowland rice
<i>Echinochloa crus-galli</i> (L.) Beauv.	<i>Echinochloa colona</i> (L.) Link	<i>Echinochloa crus-galli</i> (L.) Beauv.
<i>Echinochloa colona</i> (L.) Link	<i>Echinochloa crus-galli</i> (L.) Beauv.	<i>Paspalum scrobiculatum</i> L.
<i>Paspalum distichum</i> L.	<i>Eleusine indica</i> (L.) Gaertn.	<i>Cyperus iria</i> L.
<i>Cyperus iria</i> L.	<i>Dactyloctenium aegyptium</i> (L.) Willd.	<i>Cyperus difformis</i> L.
<i>Ischaemum rugosum</i> Salisb.	<i>Paspalidium</i> sp.	<i>Fimbristylis miliacea</i> (L.) Vahl
<i>Eragrostis japonica</i> (Thunb.) Trin.	<i>Cynodon dactylon</i> (L.) Pers.	<i>Scirpus juncoides</i> Roxb.
<i>Dactyloctenium aegyptium</i> (L.) Willd.	<i>Digitaria sanguinalis</i> (L.) Scop.	<i>Scirpus supinus</i> L.
<i>Leptochloa chinensis</i> (L.) Nees	<i>Cyperus rotundus</i> L.	<i>Sphenoclea zeylanica</i> Gaertn.
<i>Sagittaria guayanensis</i> Kunth	<i>Fimbristylis miliacea</i> (L.) Vahl	<i>Hydrolea zeylanica</i> (L.) Vahl
<i>Cyperus difformis</i> L.	<i>Eclipta alba</i> (L.) Hassk.	<i>Sagittaria trifolia</i> L.
<i>Fimbristylis tenera</i> Roem. & Schult.	<i>Trianthema portulacastrum</i> L.	<i>Monochoria vaginalis</i> (Burm.f.) Presl
<i>Eclipta alba</i> (L.) Hassk.	<i>Amisophacelus axillaris</i> (L.) Rolla Rao & Kamathy	<i>Eriocaulon sexangulare</i> L.
<i>Ludwigia perennis</i> L.	<i>Lindernia ciliata</i> (Colsm.) Pennell	<i>Ammannia baccifera</i> L.
	<i>Digera arvensis</i> Forsk.	<i>Marsilea quadrifolia</i> L.
		<i>Ludwigia perennis</i> L.
		<i>Aeschynomene aspera</i> L.
		<i>Chara zeylanica</i> Willd.

allowing weeds to emerge, grow and gain a competitive advantage over the crop; 2) early emerged weed populations will not allow rice seedlings which are still struck near the soil surface to grow normally; as the weeds get stronger and healthier the share of resources for rice diminishes; 3) there is a shift towards weed communities that require less moisture for their emergence and growth; 4) in transplanted rice, the simplification of weed flora seems to have been triggered by efforts to use more fertiliser and indiscriminate use of water. Raising productivity in transplanted rice spurred by new technology and short statured varieties encouraged farmers to adopt timely sowing and higher plant populations which favoured weeds that required high moisture and nutrient levels and could tolerate thick canopy cover.

WEED-CROP COMPETITION

The breeding of modern short statured, high yielding rice varieties and the consequent evolution of new intense cultural methods and increased fertiliser use have resulted in diminishing competitive ability of rice. Maximum yield reduction has been due to severe competition from *Echinochloa* spp.. Comparative growth studies of *Echinochloa* spp. and rice in monoculture indicated that the dark respiration rate of *Echinochloa* spp. was considerably lower (47 and 81 %) than rice. Such weeds appeared to be superior to rice in efficiently utilising the environment and producing higher biomass due to their C4 pathway of photosynthesis (Table 4).

Crop-weed competition is most severe in dry seeded upland situations and comparatively lower in puddled seeded or transplanted rice cultures (Pillai and Rao 1974). Dry weight of total weeds in direct seeded and transplanted rice as influenced by time of weed removal are given in Table 5.

Table 4. Crop growth rate (CGR), relative growth rate (RGR) net assimilation rate (NAR) of *Echinochloa glabrescens* and rice at different stages (Devendra *et al.* 1986).

Species	CGR (g/m ² /day)				RGR (g/g/day)				NAR (g/m ² /day)			
	10-20	21-40	41-50	51-65	10-20	21-40	41-50	51-65	10-20	21-40	41-50	51-65
Rice	1.9	7.6	15.2	23.2	0.134	0.097	0.061	0.048	8.53	5.64	4.30	5.81
<i>E. glabrescens</i>	4.7	12.2	28.8	61.8	0.171	0.083	0.067	0.003	10.98	5.94	6.82	11.47

Table 5. Dry weight of total weeds (g/m²) in direct seeded and transplanted rice as influenced by time of weed removal (Bhan *et al.* 1985)

Treatments	Transplanted rice	Direct seeded upland irrigated rice
Weedy check	239	412
Weed free at 15 DAT ^a /DAS ^b	124	526
Weed free at 30 DAT/DAS	41	147
Weed free at 45 DAT/DAS	30	37
Weed free at 15+30 DAT/DAS	54	145
Weed free at 15+45 DAT/DAS	23	35
Weed free at 30+45 DAT/DAS	37	23
C.D. at 5%	56	109

^aDays after transplanting; ^bDays after sowing

The first 30-40 days is considered to be the critical period for crop-weed competition in direct seeded rice (Sharma *et al.* 1977; Tewari and Singh 1991) while the removal of weeds as late as 70 days after transplanting increased paddy yield significantly (Singh *et al.* 1991).

Weeds compete severely for nutrients and depending upon the intensity of weed growth, the depletion may be up to 86.5 kg N, 12.4 kg P and 134.5 kg K/ha and in addition 61, 15, 2523 and 166 g/ha each of Zn, Cu, Fe and Mn respectively, in fields dominated by *Cyperus rotundus* L. Yield losses due to weeds in rain-fed upland rice are 50 to 97% in India (Saxena *et al.* 1990; Moorthy and Manna 1989; Vaishya *et al.* 1992), 70% in Nepal (Mallick 1982) and 80-100% in Bangladesh (BRRI 1981). Weeds in dry, wet seeded and transplanted rice caused 70-100%, 46-84 and 33-75% reduction in grain yield, respectively (Kulmi 1989). In West Bengal, an aquatic weed *Chara* sp. produced about 1060 kg/ha dry matter and removed 21.1 kg N/ha, causing a reduction in rice yield up to 41% (Guha 1991). Since long duration varieties are grown in rain-fed lowlands of Eastern India and Bangladesh, weed competition is not as severe as that in short duration rice varieties grown in uplands. Among short duration cultivars the weed competition is more in semi-dwarf than semi-tall varieties.

Wild rice causes severe problems in rain-fed lowland rice due to its competitiveness and its ability to cross-pollinate with cultivated rice. Cultivated rice seed may be contaminated with wild rice. The seeds of wild rice shatter from panicles quickly and have long dormancy. Since it is not possible to detect wild rice in the initial stages in the broadcast sown crops, farmers do not remove them. At later stages the weed becomes a problem and reduction in yield up to 15% in India was reported (Richharia 1964).

WEED MANAGEMENT

Poor weed management is the most likely cause of poor yields in rain-fed rice and direct seeded rice. The efficiency of different weed management systems is directly related to the systems of rice cultivation. Among the existing practices of rice culture, weed problems are most severe in upland rice due to direct seeding without any flooding and puddling and absence of standing water. Unless direct seeded rice is protected from a wide spectrum of weed flora, farmers have to settle for alternative crops in rain-fed areas. In upland rice, the rice and weeds emerge at the same time providing a severe competition in rice while in rice cultivation in puddled standing water, the nature and intensity of weed infestation is relatively less severe. The control measures can be divided into following categories:

Preventive Methods

1. Only clean seed should be sown. Weed control measures should be adopted in rice nurseries.
2. Keep bunds and irrigation channels free of weeds as these drop seeds into irrigation water which can carry them into the rice crop.
3. Careful tillage with complete inversion of furrow slice. This helps to remove many weeds which have grown since the last harvest.
4. Make fertiliser applications when the benefit is likely to go to the crop rather than weeds. The effect of fertiliser will be maximum if weeds have previously been removed from the crop.

Physical Methods

Weed problems vary from region to region, from farm to farm. In the Indo-Gangetic plains of India and Pakistan, where transplanted rice is the common rice culture of the wetter monsoon season from June to September, mechanical or manual weeding is not always economical. Physical methods are prevalent in the rain-fed areas or in the areas where only partial irrigation is available. In Bangladesh, Nepal, Sri Lanka, north east India, central India and to some extent southern India, moisture stress at sowing affects rice germination but weeds emerge in large number and great diversity. Moreover, hot dry winds do not allow efficient use of herbicides at sowing.

In South Asia, physical methods—manual or mechanical, have been the main practice. Starting from hand-weeding, weed control has gone through a number of stages in its evolution; use of hand tools, hoes, animal-drawn implements, employed alone or with other cultural or chemical methods as integrated weed management. Manual or mechanical methods continue to be in the mainstay in weed control in direct seeded irrigated or rain-fed and low land rain-fed rice. It is a common sight in South Asia that children and women stoop down for days together to weed their fields with hand implements. With the advent of line sowing, a number of mechanical devices and bullock or tractor drawn implements are being increasingly used for interculture and weeding. The operation of weeding between the rows leaves the weeds within rice rows uncontrolled.

In recent years, however, wages have increased to \$1 to 1.5/day in Punjab, Haryana, Andhra Pradesh and Karnataka in India, parts of Pakistan and Sri Lanka. Quite often there is a shortage of contractual or family labour at peak seasons due to their diversion to transplanting operations which

coincide with the weeding operation in uplands. Increased literacy, migration from villages to urban areas and changes in social life in villages, particularly the changing role of women in the society are fast contributing to the labour shortage. In many areas, labour is available but is utilised, in most cases, for other farm operations at the expense of weed control. The relative cost involved along with unavailability of labour during the peak periods of farm operations and tediousness of the manual operation under high temperature and high humidity are some of the drawbacks of this system. In rice nurseries, hand weeding is more difficult because in pre-germinated or broadcast seed, labourers cannot move through nursery beds without pressing down some rice seedlings.

In weed management, the main aim of the farmer is to maximise profits. For a weed control to be economical, the values of output must be greater than the resources consumed. So the choice of weed control depends on its profitability, which in turn is dependent on the costs involved in its application and the increased return resulting therefrom. In the case of manual weeding, the costs are dependent on wage rates and the efficiency of labour, while in chemical weeding it involves the prices and efficiency of herbicides. An economic analysis of weed control methods based on earlier findings in transplanted rice is given in Table 6.

Table 6. Economics of weed control practices in transplanted rice (Chaudhary 1994)

Weed control practices	Average yield (kg/ha)	Value of additional yield (\$)	Cost of weed control practices (\$)	Net return per ha (\$)
No weeding	4745	-	-	-
Butachlor	6005	155	10	145
Manual weeding 30 DAT*	5705	113	36	87

*Days after transplanting

In rain-fed upland rice, it is common practice in northern parts of West Bengal (India) and Bangladesh for farmers to pass a spike-tooth harrow (blind tillage) through their broadcast rice (Aus) fields 5-15 days after crop emergence (Moody and Mukhopadhyay 1982). In India, field experiments in rain-fed rice showed that hand hoe, blade hoe and rice weeders were as effective as hand weeding. Blind tillage often known as raking and laddering is used to lightly press, and level the soil. This operation kills some weeds as well as thinning the plant population (Ahmed and Islam 1983).

In low-land broadcast sown rain-fed rice, farmers traditionally practise an operation known as *beushaning* or *biasi* in eastern states of India- Orissa, Madhya Pradesh, Bihar and to a lesser extent in Assam, West Bengal and Uttar Pradesh. The operation involves shallow cross ploughing in water (5-10 cm depth) 30-40 days after sowing, followed by levelling. By this operation the thick population of rice is thinned and later it is followed by redistribution of seedlings and to fill gaps. During the *beushaning* operation, culms of *Echinochloa* sp. (which resemble rice plants at early growth stages but which develop internodes much earlier than long duration rice) break and detach below the nodes. Rice plants escape this damage because nodal differentiation occurs later (Biswas *et al.* 1991). This is an important low cost weed control practice in lowlands since hand weeding is expensive and impracticable. In studies on

beushaning in traditional variety (Safri 17) at Raipur, Madhya Pradesh, grain yield was highest when *beushaning* was done 45 days after sowing (Chandravanshi 1989). Improved *beushaning* involves interculturing with a cono-weeder in the inter-row spaces in drill sown crops (Sharma *et al.* 1994). Studies conducted at CRRI, Cuttack (India) revealed that the *beushaning* operation supplemented with hand weeding and gap filling increased the yield of lowland rice (Utkalprabha) by 41 % over *unbeushaned* and unweeded crops due to better weed control, crop thinning and soil loosening improving soil aeration (Moorthy and Rao 1991). No differential response of rice varieties of different plant height - Tulasi (Semi-tall), Gayatri (Semi-dwarf) and Utkalprabha (Semi-tall) to the *beushaning* operation was noticed (Moorthy and Rao 1993). This practice did not improve crop productivity where water depth went beyond 40 cm due to non-establishment of rice seedlings (Sharma 1992).

Cultural methods

In transplanted rice. *Water management.* In areas where it is possible to control irrigation, many weeds can be controlled by good water management. In all areas, it is very important that rice fields should be as level as possible since after the fields are flooded, patches of weeds may develop on odd raised pockets in the field. In most fields, continuous flooding to a depth of 5-10 cm is seldom attained. Exposure of soil surface at any time during the first 3 weeks after transplanting allows weed emergence and influences the effectiveness of herbicides.

Dry weight of weeds declines with increase in the level of submergence (Table 7). During transplanting, puddled fields should have 2.5-5.0 cm of water. After transplanting the depth may be increased to 5-10 cm. Timely and thorough withdrawing of water from rice fields helps to control algae. Drying of fields as soon as algae appears followed by reflooding is very useful for weed control. In rice nurseries, if proper depth of water (5 cm) is maintained, lower dose rates of herbicides can be used. Water management integrated with chemical weed control can achieve maximum benefits.

Table 7. Dry matter accumulation (g/m²) by weeds as influenced by the level of submergence (Singh 1983)

Level of submergence	Days after sowing			
	30	60	90	At harvest
0-5 cm	12	53	89	67
5-10 cm	12	52	72	49
10-15 cm	7	24	38	32
Direct seeded rice	144	734	693	3

Planting densities. Improved plant stand establishment and more competitive rice cultivars can help reduce weed competition. This is an important objective for breeding dry and direct seeded rice (Hobbs 1994). Medium maturity, modern short statured and high yielding rice varieties are preferred by farmers. *Basmati* rice is a major choice in Pakistan's Punjab (Byerlee *et al.* 1984), and parts of Haryana (Harrington *et al.* 1993). Tall cultivars and cultivars which cover the ground early in the season provide increased competition against weeds. Increasing crop plant density may bring about reduction in the accumulation in the dry weight of weeds (Table 8).

Increase in plant densities and nitrogen may assist each other and exert a smothering effect on weeds.

Table 8. Dry weight of weeds (g/m²) as influenced by planting densities (Walia *et al.* 1988)

Plant densities (hills/m ²)	Weed dry weight at harvest	
	1983	1984
25	26	29
33	22	26
42	18	22
50	16	20
66	12	15
C.D. (P=0.05)	3	2

Rain-fed upland rice. Unlike transplanted rice, in direct sown rice both under dry seeded condition and wet seeded condition, competition invariably favours weeds and it is difficult to control them by one or two manual weedings. Adoption of agronomic practices depending on local conditions may help to reduce weed competition in the early stages of crop growth under rain-fed upland rice ecosystems.

Stale seed bed technique. This technique in dry seeded upland rice involves the removal of successive weed flushes before planting. Chemical (paraquat or glyphosate), mechanical and manual methods may be used to control weeds. The dry seeded rice crop may be sown with minimum soil disturbance after the weeds have been controlled. The size of subsequent germinating weed cohorts will be minimised because most weeds in the favourable zone for emergence have already been controlled (Moody and Mukhopadhyay 1982). Work conducted at CRRRI, Cuttack (India) indicated that appropriate land preparation and sowing in a stale seed bed can be effectively used in integrated weed management systems (Moorthy and Manna 1988; Chandra *et al.* 1991; Moorthy 1992).

Land preparation. Ploughing immediately after harvesting the previous rice crop may have advantages over ploughing at the beginning of the next rainy season. It is possible only if the soil after harvest is still moist enough for ploughing. Repeated tillage during the fallow periods, prevents weeds from seeding and exposes vegetative propagules to drying thus depleting weed seed reserves in the soil (Moody and Mian 1979). In all the South Asian countries, rain-fed upland rice is often mono-cropped. This practice facilitates weed growth and perpetuates the weed problem for following crops (Sankaran and De Datta 1985). In eastern India and Bangladesh, pulse crops like black gram and horse-gram are often sown after upland rice on residual moisture. The crops cover the field and prevent weed growth to a certain extent.

Nitrogen application. Weed growth is stimulated if nitrogen is incorporated into the soil. Time of application should be such that competition favours the crop rather than weeds. Basal application of nitrogen aggravates weed problems in dry-seeded rice and hence, it should be

delayed until weeds have been removed. Moorthy and Mitra (1990) suggested nitrogen (60 kg/ha) should be applied in 3-4 splits after weed control.

Cultivars. Varieties that emerge rapidly, have high seedling vigour and rapidly develop a canopy cover would be expected to compete more successfully against weeds than varieties lacking these characteristics. For heavy weed infested upland situations semi-tall plant types (110-125 cm) with rapid germination, seedling vigour and moderate tillering are preferred (Mohanty 1978). Use of modern high yielding dwarf varieties coupled with high N application necessitate higher investment in weeding to realise higher yields.

Seed rate and sowing methods. Sowing in rows and high seed rates reduces weed growth, increases crop plant population and increases grain yield of rice over broadcast sowing (Chandrakar *et al.* 1985). Tosh *et al.*, (1981) observed reduction in weed biomass with increasing sowing rates from 70 to 110 kg/ha. Moorthy and Mitra (1991) also recorded similar reductions with increasing sowing rates from 50 to 100 kg/ha. Rice establishment methods have a great effect on weed problems encountered during the season. Maximum weed populations and dry weights are found in dry seeded rice and minimum population and dry weight are found in the transplanted rice (Table 9).

Table 9. Effect of different rice stand establishment methods on density and dry weight of weeds at harvest (Shah *et al.* 1990)

Rice stand establishment methods	Weed density (no/m ²)	Weed dry weight (g/m ²)
Direct seeding	15.6 (278)	163.8
Sprouted seed in puddled condition	13.6 (205)	109.9
Transplanting	11.0 (137)	89.0
C.D. at 5%	0.2	7.3

Plant density and row spacing. Wider spacing of 60 cm increased weed incidence (Pillai and Sreedevi 1980) and a closer spacing of 15 cm was found successful both from the point of view of crop growth and weed suppression (Pande *et al.* 1974).

Chemical Weed Control

Transplanted rice. Chemical weed control has largely been accepted by farmers of transplanted rice but not by farmers of direct seeded irrigated, direct seeded rain-fed and rain-fed lowland rice conditions. The more popular herbicides include butachlor, thiobencarb and anilofos. Other herbicides which have been found successful include, pretelachlor, cinmethaline, chlorimuron, pendimethalin and metsulfuron. Sulfonyle urea herbicides have been found effective against annual broad leaf weeds. These herbicides can be used for broad spectrum weed control tank mixed with grass killing herbicides. In India herbicide use in transplanted rice started in the mid seventies and increased to 540 MT. (active ingredient) in 1983. By 1993 the use of butachlor, anilofos and thiobencarb was 1860, 450 and 10 MT. active ingredient, respectively. In transplanted rice, herbicides applied alone 3-4 days after transplanting are quite successful because the weed flora is dominated by annual sedges and grasses. Chemical weed control is

more economical in transplanted rice situations of north-west India and parts of south India and Pakistan. The acceptance of chemical weed control depends on the stage of agricultural development. Since north-west Indian farmers with the best lands for rice cultivation have already adopted new cultivars and fertilisers at more than 120 kg N/ha, chemical weed control is the best alternative to increase or stabilise paddy yields.

Direct seeded irrigated upland rice. In upland direct seeded rice, a short season dry seeded rice is grown during the monsoon. This system is followed in small areas in Indo-Gangetic plains where a subtropical climate prevails. Most often dry seeding is done after one pre-sowing irrigation in the month of June. Early emergence of weeds along with crop seedlings and their rapid growth results in a severe crop weed competition and this culminates in greater reduction in the growth and yield of rice crop as compared to transplanted rice ranging from 74 to 100 % (Poonia 1983). Pendimethalin at 1.5 kg/ha or thiobencarb at 2 kg/ha have been found to effectively control weeds in upland direct seeded irrigated rice. However, two manual weeding have been found to provide better weed control than herbicides (Bhan *et al.* 1986). In this system a wide spectrum weed flora of annuals and perennials (*Cyperus rotundus*) occurs so that either herbicides or mechanical control alone may not be successful. Herbicide mixtures applied at post emergence and supplemented with one manual weeding are needed for successful weed management.

Rain-fed upland rice. Herbicides which have been found effective in this system include; propanil applied post-emergence, butachlor applied pre-emergence, butachlor applied pre-emergence and supplemented with one hoeing, oxadiazon applied alone as pre-emergence and supplemented with one hoeing, oxyflourfen applied alone and supplemented with one hoeing, pendimethalin applied alone and supplemented with one hoeing. Experiments conducted in different parts of India are summarised in Table 10.

Herbicides found most effective in south India include pendimethalin and thiobencarb while in central and north India pendimethalin was found most effective. Most pre-emergence herbicides have been found to cause phytotoxicity problems on rice seedlings whenever heavy rains occurred immediately after their application indicating adverse herbicide-moisture interaction (Moorthy and Mitra 1991). Effects on the selectivity of herbicides due to genetic variability has been reported from many experiments conducted in rain-fed upland rice (Mohan and Subrahmanian 1976; Moorthy and Manna 1984). Toxicity caused by butachlor at 2.0 kg/ha in upland rice was minimised by hand placement of activated charcoal, an absorbent @ 50 kg/ha and next best was seed pelleting with activated charcoal @ 2 kg/ha (Moorthy and Mitra 1992). The latter method was more economical. Use of safener (0.189 kg/ha) along with the herbicide butachlor (1.25 kg/ha) was found to reduce toxicity on rice seedlings and increase yield (Murthy *et al.* 1993).

Rain-fed lowland rice. Most available information from South Asia indicates that herbicides suited in upland rice can be conveniently used in the rain-fed lowland ecosystem. In a majority of the cases herbicides applied alone are not economically viable and one manual weeding is necessary. Supplementing the *beushaning* practice with oxadiazon (0.6 kg/ha) or thiobencarb (1.5 kg/ha) gave the highest weed control efficiency (Prusty *et al.* 1988).

Table 10. Effect of weed control methods^a on the grain yield of rice under direct seeded upland conditions (Angadi *et al.* 1993; Sreedevi and Thoma, 1993; Mahalle *et al.* 1993; Jena *et al.* 1993; Prusty *et al.* 1993; Saxena and Vaishya 1993)

Weed control methods	Grain yield (kg/ha)							
	Southern India				Central India		North India	
	Karnataka		Kerala		Maharashtra		Orissa	
	(1990)	(1991)	(1991)	(1992)	(1991)	(1990)	(1991)	(1989)
Unweeded check	60	510	778	960	1120	1580	200	121
Weed free check	5880	2640	-	-	-	-	-	4233
Two hand weedings	3600	2340	5956	3506	2587	3070	1800	2998
Herbicide + manual weeding	-	2230	-	-	-	-	1700	3459
Herbicide alone	730	1570	4889	2722	2286	3310	1200	2919
C.D. (P=0.05)	530	410	1552	812	-	293	600	125

^a Best treatments of herbicides and herbicide + manual weeding were included in the summary.

CONTROL OF AQUATIC WEEDS

Because of water depth, application of chemicals for aquatic weed control is beset with problems. In West Bengal (India) the troublesome weed *Chara*, could be effectively controlled by oxadiazon applied pre-emergence at 2 kg/ha or CuSO₄ at 16 kg/ha. CuSO₄ at 10-12 kg/ha also gave satisfactory control of floating and algal weeds (Dutta and Banerjee 1980; Pande 1984). More research is needed to discover cost effective aquatic weed control methods in lowland rice culture.

CONTROL OF WILD RICE

Since wild rice causes significant yield reductions in domestic rice, farmers in eastern India generally prefer to grow purple leaf cultivars of rice where wild rice is a problem. This facilitates weeding out wild rice. However, these purple leaf cultivars are not as good yielders; purple stemmed cultivars with green foliage are better (Richharia 1964). High yielding purple stemmed varieties are rare. Recently a cultivar, Kalashree, was developed at CRRI, Cuttack and is well suited for wild rice infested situations. Other improved cultivars earlier developed in Orissa (India) were T 1145 and T 1242. However, since wild and domestic rice can cross-pollinate, it is possible that wild rice may also develop populations with purple leaves or stems. Wirjahardja *et al.* (1983) and Richharia (1964) recommended the following measures to minimise wild rice competition:

- By sowing pre-germinated seed in fields that have been flooded or cultivated.

- By transplanting rice in lines after puddling the field to (a) destroy the germinating wild rice that may exist at the time of transplanting and (b) to enable the detection of wild rice plants so that they can be rogued out as they appear.
- By puddling the soil before broadcasting rice seed.
- By row seeding where rice growing between rows can be easily recognised and weeded out.
- By growing short-season rice varieties that are harvested long before wild rice shatters its grains.

The challenge for weed management in both upland and lowland rice is to put together a package of technology that most farmers can use. Herbicide application techniques in South-Asia show considerable room for improvement.

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CHAPTER 10

WEED MANAGEMENT IN RICE IN THE NEAR EAST

WEED MANAGEMENT IN RICE IN THE NEAR EAST

S.M. Hassan and A.N. Rao

INTRODUCTION

Rice is the traditional staple food of the Near East, particularly for the Egyptian and Iranian peoples. Their agriculture has long concentrated on rice production but rice is a new crop in Morocco, Sudan and Saudi Arabia. Rice is grown in 1,411,000 ha in the Near East (FAO 1993). Egypt, Iran, Iraq and Turkey are major rice growing countries in the Near East with areas of 510,000, 600,000, 75,000 and 53,000 ha respectively (Table 1).

Table: 1. Area under rice (1992) and productivity of rice in the Near East*.

	Area ('000 ha)	Yield (kg/ha)
World	147168	3571
Near East	1411	5013
Egypt	510	7659
Iran	600	4164
Iraq	75	2000
Turkey	53**	4340**
Morocco	6.6***	3470***
Syria	2**	5500**
Sudan	1**	1000**

Source:

* FAO, Quarterly Bulletin of statistics. 1993. Vol.6, No: 2. Page: 28.

** FAO 1991. *AGROSTAT* Information system of Food and Agriculture Organisation, Rome.

*** Lakrimi 1992

Transplanting and broadcast seeding are the major systems of rice establishment in the Near East. Rice is transplanted in Iran (90 to 94%) (Izadyar 1992) and Egypt (70 to 75%) (Hassan and Rao 1993b) while it is direct seeded rice in Turkey (100%) (Nezihi 1994), Sudan (100%) (Simbe 1992), Iraq (100%) and Morocco (90 to 97%) (Lakrimi 1992). In recent years, direct seeding (broadcasting or dibbling pregerminated seeds on puddled soil) has become an increasingly important method of rice establishment in many countries. For example in Egypt, about 25 to 30% of the rice farmers have switched to broadcast and/or dibbled seeded rice. The average productivity of rice in the Near East is 5013 kg/ha compared with 3,570 kg/ha for the world (FAO 1993). Egypt ranks first in productivity in the region with 7,659 kg/ha, while the productivity of rice in Iran, Iraq, Turkey was 4164, 2000, and 4340 kg/ha, respectively (FAO 1993). In experiment stations in Egypt productivity of up to 13 t/ha has been recorded (Balal 1992). The favourable environmental factors in the Near East are not only conducive to rice but also to the weeds. Hence weeds are one of the major limiting factors in rice production in the region.

In this chapter, the research progress on weeds and their management in rice in the Near East is reviewed, the sustainable weed control measures useful to the farmers are summarised and future weed management research needs are proposed.

WEED FLORA

Rice fields can be colonised by terrestrial, semi-aquatic or aquatic plants depending on the type of rice culture, the season and environment. Rice fields, in general, support a diverse flora with diversity decreasing with increasing flooding and puddling. This colonisation occurs despite the drastic intervention required to prepare the fields for planting (Fernando 1980).

Zohary (1973) noted that the eastern and southern fringe of Mediterranean and adjacent Iran-Turanian steppes in the Middle East are the largest centre for weeds and are the cradle of many weeds common to the temperate and warm temperate zones of the world.

A review of the literature and the response of the scientists to a structured questionnaire from us revealed that, the rice fields in the Near East are infested with about 65 weed species from 25 genera. The most widespread weed species belong to Poaceae and Cyperaceae. *Echinochloa crus-galli* (L.) P. Beauv. and *Cyperus difformis* L. among annuals and *Scirpus maritimus* L. and *Cyperus rotundus* L. among perennials were the most commonly reported species in the Near East. The major weeds occurring in rice fields in different countries of Near East are presented in Table 2.

Shifts in Weed Floras

Ecological shifts in weed populations are known to occur in rice agroecosystems due to changes in cropping systems, use of herbicides, continuous use of a cultural method or a change in the method of planting rice.

Most herbicides have always controlled the weeds for which they were intended but leave other species uncontrolled. These weeds later become troublesome. In Egypt, the continuous use of thiobencarb in the Dumaita governorate has led to the predominance of *Ammannia* spp. and *Eclipta prostrata* (L.) L. In Dakhalia governorate, it has led to the shift in population to *Echinochloa colona* (L.) Link and *Eleocharis geniculata* (L.) Roem. & Schult.. In the Kafr El Sheikh and El-Sharqia governorates, continuous use of oxadiazon led to the predominance of *C. difformis* and *Scirpus juncoides* Roxb.

The change from manual transplanting to broadcast seeded rice has resulted in dramatic shifts in weed infestation and distribution. The *Echinochloa* spp. population has increased with the increase in broadcast seeded rice in Egypt. For example in the Dakhalia governorate (which has the largest area under broadcast seeded rice), the hierarchical list of dominance is in the order of *Echinochloa* spp., *Cyperus* spp. and *Ammannia* spp.

In Iran, application of herbicides by farmers is often supplemented by hand-weeding to remove uncontrolled weeds. Farmers managed to stop shifts in weed flora with this practice even after 15 years of continuous application of herbicides (Moussavi 1985). However, *Echinochloa crus-galli* became resistant to propanil (Moussavi *et al.* 1989). *Monochoria vaginalis* (Burm. f.) Presl which was first found in Iran, in 1989 (Sharif 1990), has spread from 500 ha in 1989 to 1,000 ha in 1991 (Izadyar 1992); it is most common in Gilan Province of Iran.

Table: 2. Commonly reported troublesome weed species in rice in the Near East.

Weed species	E G Y P T	I R A Q	I R A Q	T U R K Y	M O R O C C O	S A U D I A	S A U D I A
<i>Echinochloa crus-galli</i> (L.) P. Beauv.	+	+	+	+	+		+
<i>Echinochloa oryzoides</i> (Ard.) Fritsch.	+						
<i>Echinochloa phyllopogon</i> (Stapf) Koss.	+				+		
<i>Echinochloa colona</i> (L.) Link	+	+	+	+		+	
<i>Dinebra retroflexa</i> (Vahl) Panzer	+					+	
<i>Diplachne fusca</i> (L.) P. Beauv. ex Roem. & Schult.			+				
<i>Brachiaria eruciformis</i> (J.E. Sm.) Griseb.						+	
<i>Cyperus difformis</i> L.	+	+	+	+	+		
<i>Cyperus rotundus</i> L.	+	+	+	+			+
<i>Cyperus fuscus</i> L.		+		+	+		
<i>Scirpus juncooides</i> Roxb.	+	+		+			
<i>Scirpus maritimus</i> L.	+	+	+	+	+		
<i>Scirpus litoralis</i> Schrad.		+	+				
<i>Fimbristylis bis-umbellata</i> (Forssk.) Bub.		+					
<i>Eleocharis geniculata</i> (L.) Roem. & Schult.	+						
<i>Ammannia baccifera</i> L.	+						
<i>Ammannia auriculata</i> Willd.	+		+				
<i>Ammannia multiflora</i> Roxb.	+	+					
<i>Alisma plantago-aquatica</i> L.		+		+			
<i>Heliotropium sudanicum</i> F.W. Andrews						+	
<i>Phyllanthus fraternus</i> Webster						+	
<i>Leucas urticifolia</i> L.						+	

Source: **Egypt:** Hassan and Rao 1993 a and 1994 b. **Iran:** Izadyar 1992, 1994; Dastgheib and Beigi 1988; Bischof 1971; Moussavi 1985; Fatemi 1983. **Iraq:** Najjar 1994; Abdullah *et al.* 1986; Hussain and Kasim 1976. **Turkey:** Nezihi 1994; Yiliz 1994; Hatice 1994; Kurcman 1985. **Morocco:** Tanji 1994; Lakrimi 1992, 1994; Mouch 1985; Bouhache and Bayer 1989, Bouhache *et al.* 1989. **Sudan:** Babiker 1982; Ghobrial 1981; Hamdoun and Babiker 1978. **Saudi Arabia:** Chang *et al.* 1976.

CROP YIELD LOSS ASSESSMENT

Weeds cause greater yield losses in direct seeded rice than in transplanted rice and in dry seeded soil than in puddled seeded soil (Moody 1977). In the Gilan province of Iran, weeds cause more yield losses than diseases and insects (Mirkamali 1985). In Egypt, farmers ranked weeds as more troublesome than other pests (Hassan and Rao 1993a). The annual average reduction in rice yield in Arab countries is about 14% (Anon 1984).

In Egypt, the potential yield loss due to uncontrolled weeds ranged from 4.42 to 7.6 t/ha with an average yield loss of 6.67 t/ha (75%). In manually transplanted rice the yield loss was minimum (46%) when compared with 90% losses with direct seeded rice (Hassan and Rao 1993a). However when weeds were controlled to different degrees, each 100 g/m² dry weight of survived weeds (comprising 75% grasses and 25% sedges and broad leaf weeds) reduced grain yield by 18.5%.

Crop losses due to weeds were estimated as 50% for rice in Iraq (Abdullah *et al.* 1986; Al-Kaisi 1987). The competition of weeds reduced grain yield of irrigated direct seeded rice in Sudan by 50 to 75% (Babiker 1982; Hamdoun 1985; Ghobrial 1981) and 30 to 65% in Turkey (Nezihi 1994; Yildiz 1994; Hatice 1994; Kadri 1994). In Morocco, rice yield losses were reported to range between 30 to 100% under high densities of *E. crus-galli* (Tanji 1994; Lakrimi 1994; Abdellah 1994).

In Iran, 128 plants/m² of *E. crus-galli*, *C. rotundus* and *C. difformis* reduced grain yield of transplanted rice by 19% (Dastgheib and Beigi 1988). In Gilan province of Iran, 256 plants/m² of *E. crus-galli*, *C. difformis*, and *Scirpus maritimus* reduced the rice yield by 30% (Mirkamali 1985).

THRESHOLD LEVELS

Studies on economic threshold levels in the Near East are meagre. In Egypt, on an average one *E. crus-galli*/m² caused an 11% reduction in rice grain yield (Hassan and Rao 1994a). When rice plants grew between *E. crus-galli* plant groups spaced 20, 40, 60, 80 and 100 cm apart, rice grain yields were reduced by 59, 54, 50, 28, and 21% respectively. The results indicated that patchy distribution of barnyardgrass which survived herbicide or other weed control measures would result in rice yield reduction. Thus, uniform *E. crus-galli* control is needed to avoid rice yield losses.

METHODS OF WEED CONTROL

Preventive

Preventing the establishment of weeds through dissemination by different means on farm is important in rice even today as it was before the advent of herbicides.

Planting of clean seed is perhaps the most important management technique to minimise losses (Stoskopf 1985; Rao and Moody 1990). Use of weed free certified seed prevents the dissemination of weeds with seed. A survey in Egypt revealed that certified seed is usually relatively weed seed free, but farmers' seed was rarely completely free from weed seeds (1.8 to 4.5% weed seeds). In Iraq, the contamination of *Echinochloa* species seeds in rice seed is a problem (Abdullah *et al.* 1986) and it lowers the planting value of rice to great extent. In Egypt certified seed is available every year for 60-80% of the rice area (Balal 1993). In Morocco one of the major concerns is the lack of certified seed (Lakrimi 1994). Use of clean equipment, burning and other preventive measures should also be encouraged.

Cultural Methods

Every cultural operation is a selection process designed to encourage the crop, but specialised weeds are encouraged by the same process. Cultural practices selectively favour weeds despite the best efforts of the cultivator (Harlan 1975).

Method of rice crop establishment. Transplanting rice seedlings (3 to 5 weeks) with five leaves or at tillering stage and their tolerance of flood water confers a competitive advantage over weeds and this is the major reason for transplanting rice in Egypt (Ibrahim and Hassan 1986) and Iran (Izadyar 1992; Moussavi 1985).

Seedling age, spacing and number of seedlings/hill. In Iran, 20 to 25 day-old seedlings at a density of 16 to 20 hills/m² with 3-5 seedlings/hill are recommended for optimal grain yield (Izadyar 1992). In Egypt, 30 day-old seedlings were found superior to older seedlings. In narrow spacings (10-20 x 20 cm), weed competition was reduced, herbicide performance was increased when compared with wide spacing (Hassan *et al.* 1991c). The combination of continuous flooding, close spacing (10x20 cm) and six seedlings per hill resulted in complete suppression of weeds and highest grain yield eliminating the need for herbicide (Hassan and Rao 1993c). Narrow spacing with optimal nitrogen (96 kg/ha) and thiobencarb 2.4 kg/ha suppressed weeds optimally under the recommended irrigation regime and produced the highest yield (Hassan and Rao 1993c).

Seeding rate. Crop competition is one of the cheapest and most useful methods of weed control available to farmers and is complementary to other methods. The closer rice plants are sown, the more competitive they would be against weeds and less weeds that grow in association with them (Hassan *et al.* 1990a, Hassan and Rao 1994a). In Egypt, research revealed that 400 seedlings/m² in broadcast seeded rice will provide optimum yield, while the farmers maintain about 600 to 700 seedlings/m². A high sowing rate of 192 kg/ha is recommended in broadcast seeded rice to control broadleaf weeds and *C. difformis* (Hassan *et al.* 1990a). In broadcast sown rice, the recommended sowing rate is 130 to 175 kg/ha in Iran (Izadyar 1994; Mirkamali 1994), 160-200 kg/ha in Turkey (Hatice 1994), 100-120 kg/ha in Iraq (Abdullah *et al.* 1986) and 200-300 kg/ha in Morocco (Tanji 1994; Lakrimi 1992, 1994). A high sowing rate is used by rice farmers transplanting in Egypt and Iran to compensate for bird damage and to suppress weeds.

Water management. Lack of water is a major constraint to rice production. A cause of water shortage is often due to weeds (Navarez *et al.* 1979). Flooding is effective and economical to control some weeds. Exposure of the soil to dry conditions for 8 to 12 days in the early stages of rice growth increased weed number, the time required for hand weeding, the severity of weed competition and reduced the efficacy of the applied herbicide (Table 3) (Hassan *et al.* 1991b). Most of the herbicides in Egypt and Iran are applied in standing water which should be maintained for 3-5 days.

Land preparation. a) Stale seedbed technique: The most practical and widely used means of weed control in Iraq is the stale seedbed technique (Abdullah *et al.* 1986). Fields are generally irrigated 10-15 days before sowing. This promotes weed germination and growth. After the optimum soil moisture is reached, a disc harrow is run and the crop seed is sown.

Stale seedbed is recommended in mechanically transplanted and drill seeded rice in Egypt to reduce weed pressure (Hassan and Mahrous 1989). Paraquat 0.6 kg/ha at 3 days before planting is used when weeds have reached 3-leaf stage. Shallow harrowing is recommended before drilling rice.

b) Tillage: In Egypt, the lowest density of weeds was reported with land preparation by mouldboard ploughing+disc harrowing+dry levelling (El Serafy *et al.* 1994). In the Sudan, land

Table: 3. Dry weight of weeds and grain yield of rice as influenced by herbicides applied under different water regimes in manually transplanted rice (Hassan *et al.* 1991b).

Herbicides, kg ai/ha	Water regimes			
	Continuous flooding	4 days on+ 4 days off	4 days on+ 8 days off	4 days on+ 12 days off
Weed dry weight (g/m²):				
Weedy check	60j	288de	597b	715a
Weed free	0k	0k	0k	0k
Thiobencarb, 2.4	2k	62j	165gh	255c
Thiobencarb, 3.6	1k	17k	120i	175f
Butachlor, 2.9	0k	40j	148g	245cd
Oxadiazon, 0.6	0k	41j	132h	208e
Grain yield (t/ha):				
Weedy check	8.5i	4.1f	0.7b	0i
Weed free	11.1a	11.1a	8.9c	6.0d
Thiobencarb, 2.4	11.0a	10.1b	5.0f	2.9g
Thiobencarb, 3.6	11.0a	10.8a	6.6d	4.5f
Butachlor, 2.9	11.0a	10.0b	5.0e	3.3g
Oxadiazon, 0.6	11.0a	10.1b	5.0e	3.1g

* In a column, means followed by a common letter are not significantly different at the 5% level by Duncan's Multiple Range Test. ; Herbicides were applied 4 days after transplanting.

preparation consists of discing and ridge operations. In rain-fed areas, farmers use simple cultural practices (Hamdoun 1985). Precise land levelling (dry or puddling) is required to maintain uniform water depth, good stand establishment, better herbicide efficacy and optimal weed suppression. Hence, in Egypt laser levelling will benefit large area farmers growing direct seeded rice.

Nitrogen. The application of nitrogen without proper weed management tends to enhance vigour and competitive ability of weeds. In experiments conducted at a rice station in Egypt, in a weedy check treatment, increasing nitrogen from 96 to 144 kg N/ha increased weed dry weight by 44 to 54%. Increasing nitrogen levels increased the grain yield significantly when herbicides were used as it enhanced the competitive ability of the crop against surviving weeds (Hassan and Rao 1994a).

E. crus-galli weight was increased by 25% in association with short statured cv: Giza 181 when compared with long statured cv: Giza 171 under nitrogen level of 192 kg N/ha (El Kalla *et al.* 1989). Ghobrial (1983) reported consistent and progressive increase in grain yield of rice with increase in nitrogen level associated with better weed management.

Physical Methods of Weeding

Hand weeding. Hand weeding is still the common control method used by most rice farmers in the Near East. Two hand weedings, correctly timed, provide excellent weed control in

transplanted rice, while hand weeding is much more difficult and slower in direct seeded rice because of high weed densities and similarity between rice and grass weed seedlings.

Hand weeding is effective when the weeds are at the seedling stage but ineffective against established weeds. Kukula (1985) mentioned that in the Near East, hand pulling is commonly used at a very late stage of growth and weeds have already competed with the crop. Late weeding does not help to increase crop production but provides a good quantity of fodder to feed livestock. Likewise in Egypt, hand weeding is delayed until most of the weeds are easily observed.

Prior to 1982 in Egypt, weeds in paddy fields were controlled mostly by manual weeding. In 1991, our survey disclosed that hand weeding was used in 40 to 50% of the area and often integrated with herbicides. In Iran 95% of fields are hand weeded either alone or in combination with herbicide application (Izadyar 1994), while in Morocco rice fields hand weeding is the only method of weed control (Lakrimi 1992). In 15 to 20% and 25% rice area of Turkey (Yildiz 1994) and Iraq (Najjar 1994) respectively, hand weeding is used. In Sudan, the application of herbicide is preferred to hand weeding to avoid additional cost (Hamdoun and Babiker 1978).

In Iran, control using herbicides and hand weeding is practised by farmers. Weeding is generally done twice by application of herbicide and by hand by women in Gilan province and by men in Mazandaran province (Izadyar 1992). In transplanted rice in Iran, two hand weedings at 15 and 25 days after transplanting, with 15 and 10 labourers respectively/ha required (Moafizad *et al.* 1977). In Egypt the first hand weeding is recommended at 20-25 days after transplanting and the second hand weeding after two weeks, requiring on an average 50 and 30 labourers/ha respectively.

In broadcast seeded rice in Egypt, three hand-weedings are required, at two week intervals, starting from 20 days after sowing. The average labour requirement is between 100 to 150 hours/ha. The labour requirement for hand weeding after herbicide application is about 40 to 50 labour hours/ha. Five labour days/ha is recommended in Turkey (Yildiz 1994; Kadri 1994). In Morocco, 1000 labour hours are needed/ha for hand-weeding (Lakrimi 1994).

Herbicides

Herbicides will continue to be a key ingredient in integrated weed control systems in rice, especially in direct seeded rice in Egypt, Sudan, Turkey and Iraq because no adequate substitutes currently exist (Hassan and Rao 1994a; Hassan *et al.* 1991a, b; Babiker 1982; Kurcman 1985; Yildiz 1994). In most of the Near East countries, herbicides play an important role in rice production, but they are not the sole method to combat weeds. They are most effective when used in combination with other control methods, especially water management (Hassan *et al.* 1991b; Moussavi 1985; Abdullah *et al.* 1986) during the early stages of weed growth and/or hand-weeding (Table 3). Use of more than one herbicide gives more effective and longer lasting weed control with less or without additional hand weeding (Kadri 1994; Hassan and Mahrous 1989). Different herbicides are recommended for weed control in different countries for transplanted and broadcast seeded rice.

In Egypt, since the 1980's herbicides have played a major role in farmers' weed management schemes. In 1988, 860 tons of rice herbicides were imported and the area treated with herbicides increased in 1989 (Balal 1990). The area treated with herbicides started to decrease from 1990

(55% in 1988) to about 20% in 1992. The cutting of a subsidy on herbicides is the only reason for this reduction. The common herbicides used by farmers in Egypt are thiobencarb at 2.4 kg/ha at 2-leaf stage in nursery and broadcast seeded rice and 3-4 days after transplanting in transplanted rice (Anon. 1993). However, experimental studies revealed that thiobencarb is most effective at 3.6 kg/ha when applied in two applications of 1.8 kg/ha each at 4 days before seeding (DBS) and as early post emergence application in broadcast seeded rice (Table 4). Oxadiazon also was found effective when applied in two applications 0.24 to 0.3 kg/ha at 4 DBS and 0.24 to 0.3 kg/ha 7-8 DAS. Bensulfuron-methyl at 0.4 kg/ha is effective against sedges and broadleaf weeds. Butachlor at 1.45 kg/ha is also effective in managing weeds in broadcast seeded rice (Table 4) and was accepted by farmers. In transplanted rice, oxadiazon, 0.45 or butachlor, 2.1 kg/ha are two common herbicides used by farmers in Egypt and are applied at 3-4 DAT. Early treatment is necessary to achieve satisfactory control of weeds. The combination treatment of thiobencarb + propanil, 2.4+1.8-2.6 kg/ha or the application of pendimethalin, 2.0 kg/ha applied as early pre-emergence or early post-emergence plus hand weeding are recommended for drill seeded rice in Egypt.

Seedlings of *Echinochloa* species cannot be easily distinguished from rice seedlings in nurseries. Often *Echinochloa* species are unintentionally transplanted with rice seedlings they are morphologically similar. Transplanted *Echinochloa* species are highly competitive (Rao and Moody 1992) and are difficult to control manually (Rao and Moody 1987). Experiments at RRTC, Egypt indicated application of molinate, 6.0 kg/ha at 3 DAT or fenoxaprop-p-ethyl at 0.063 kg/ha applied at 7 to 12 DAT are effective in controlling transplanted *Echinochloa* species (Hassan and Rao, unpublished).

In Iran, about 90% of the rice area is treated with herbicides (Izadyar 1994); the government subsidises 80% of the herbicide cost (Mirkamali 1994). About five herbicides are recommended in nursery seed-beds (Jafari and Moussavi 1993; Moussavi 1985) but the commonly used herbicides are molinate at 3.5 to 4.5 kg/ha at 1 to 1.5 leaf stage of rice or soil incorporation, 3 DBS, and propanil at 4.5 to 5 kg/ha at 1.5 to 2 leaf stage of *E. crus-galli*. In transplanted rice, eight herbicides are recommended (Izadyar 1994; Mirkamali 1994; Fatemi 1990; Moussavi *et al.* 1989). The common herbicides used by the farmers in transplanted rice are butachlor, 1.8 to 2.4 kg/ha, oxadiazon, 0.36 to 0.48 kg/ha, all applied at 3-7 DAT and propanil, 5.4 kg/ha applied at 2-4 leaf stage of *E. crus-galli*.

In Iran, in a 3-year study at Esfahan, applications of thiobencarb at 3 kg/ha applied 3 days before sowing or post-emergence. Twenty five days after sowing (DAS), thiobencarb at the same rate + 2,4-D at 1 kg/ha 25 DAS, thiobencarb + propanil at 3.5 + 4.2 kg/ha, resp., 15 DAS and 3.5 kg/ha of molinate 10 DAS + 1 kg/ha of 2,4-D 25 DAS were found to be effective in controlling *E. crus-galli*, *Ammannia multiflora* Roxb., *C. difformis*, *Cyperus longus* L., *Polygonum persicaria* L. and *Alisma lanceolata* in direct-sown rice fields (Fatemi 1990).

Several experiments conducted in direct-sown (pre-germinated seed) flooded rice at Rasht, Iran revealed that propanil, unsuitable because of application problems and the persistence of *Echinochloa crus-galli*, was best applied in a mixture or followed by a residual soil-applied herbicide such as molinate or thiobencarb (Moussavi *et al.* 1989). Molinate, 3.5-4.5 kg/ha incorporated pre-sowing or post-emergence at the 2-leaf-stage of *E. crus-galli* gave good weed control and crop tolerance was good, but it was essential that the field was kept flooded and that

Table 4. Weed dry weight, grain yield and marginal benefit cost ratio of broadcast seeded rice as affected by herbicide application four days before seeding. RRTC. 1991 and 1992 (Hassan and Rao 1993b).

Treatments	Weed dry weight (g/m ²)		Yield (t/ha)		Marginal benefit cost ratio	
	1991	1992	1991	1992	1991	1992
Weedy check	385a	349a	0.42e	0.63e	-	-
Weed free	0d	0i	9.97a	9.72ab	4.3	6.8
Thiobencarb (2.4) EPOE f.b.	67bc	77bc	8.26cd	8.63b-g	9.4	13.0
HW	60bc	70b-e	8.92bc	7.21h	29.3	18.8
Thiobencarb (2.4) PS	46c	33f-i	9.03bc	9.13a-d	21.1	16.3
Thiobencarb (3.6) PS	41c	6i	9.24b	9.56ab	21.1	17.1
Thiobencarb (1.8) PS f.b.(1.8) EPOE	93b	84bc	8.04b	7.96c-h	8.9	16.1
Oxadiazon (0.45) PS	74bc	52d-g	8.73c	8.98a-c	28.1	44.7
Oxadiazon (0.3) PS f.b. (0.3) EPOE	57bc	14h-i	9.01bc	9.44ab	15.8	35.6
Butachlor (1.45) PS	60bc	4i	8.93bc	9.54a-c	42.7	75.3
Butachlor (1.2) PS f.b. (1.2) EPOE	47c	9i	8.98bc	9.31e-h	26.7	46.3
Dithiopyr (0.12) PS	73bc	67c-e	8.24d	7.94c-g	-	-
Dithiopyr (0.12) + Sindax (0.01) PS	95b	99b	8.75c	8.37a-c	-	-
Molinate(4.3)+ Bensulfuron methyl (0.05) PS	61bc	8i	9.19b	9.23ab	-	-

Within a column, means followed by a common letter are not significantly different at the 5% level by Duncans Multiple Range Test.

* Rate in Kg ai/ha is given in parentheses; DBS=Days before seeding; PS= Pre seeding; EPOE= Early post emergence application; f.b.= followed by; HW= Hand weeding. - = Herbicide rate not available.

water remained undisturbed for 3-4 days. Thiobencarb applied 3-5 days before sowing or post-emergence at the 2-leaf-stage of *E. crus-galli* was effective and the crop damage and stand reduction resulting was acceptable. It was necessary to apply 2,4-D, bentazone or 2,4-D + MCPA to control sedges.

In Iraq, 75% of the direct seeded rice area is treated with herbicides (Najjar 1994; Abdullah *et al.* 1986; Anon 1981). The government subsidises herbicides and the equipment. Propanil, 2.5 kg/ha at 1-3 leaf stage of *E. crus-galli* and molinate at 4.3-5.8 kg/ha soil incorporated before planting are used widely by the farmers (Najjar 1994; Abdullah *et al.* 1986; Anon. 1981).

In the Sudan, herbicides are required to avoid Bilharzia infection. Oxadiazon at 0.5-0.9 kg/ha, 3 days after seeding is promising against common weeds. Thiobencarb at 1 kg/ha propanil, 1.5 kg/ha and bentazon, 1.2 kg/ha were used by farmers with follow-up hand-weeding (Babiker 1982; Ghobrial 1981).

In Turkey, about 80% of the broadcast seeded area is treated with herbicides. Propanil, 3.25-5.40 kg/ha at 2-3 leaf stage is applied in 40% of the area while molinate, 3.6 kg/ha as preplanting is applied in the rest (Nezihi 1994; Yildiz 1994; Hatice 1994). Thiobencarb, propanil + bentazon, propanil + oxadiazon, bentazon, MCPA, paraquat, propanil + molinate, propanil + quinclorac and bensulfuron methyl were also tested in Turkey and recommended.

In Saudi Arabia, where transplanted rice is common, thiobencarb-CNP, 3.9 kg/ha was found to be best to control mixed weed populations (Chang *et al.* 1976).

Application of herbicides. Herbicides must be properly placed in relation to the crops and weeds and be adequately and evenly distributed if they are to be effective weed control tools (Hassan *et al.* 1990b).

In drill seeded rice in Egypt, a helicopter-boom sprayer made accurate, uniform application giving excellent weed control and grain yield (Hassan *et al.* 1990b). Spray application of herbicides was better than their application in a gypsum carrier in transplanted rice (Ibrahim and Hassan 1986). The majority of the farmers in Egypt reported use of herbicides in nursery, broadcast seeded rice and transplanted rice with sand or soil carrier on to flood water (Hassan and Rao 1992).

In Iran, herbicides are usually applied in transplanted rice by sprinkling them directly from the bottle on to the water, the resulting performance being equal to that obtained with a knapsack sprayer (Moussavi 1986). Application of undiluted herbicides into the flood water eliminates equipment such as the knapsack sprayer which requires large quantities of water; this reduces both manpower requirements and the cost of herbicide application. In Iraq, the government subsidises the herbicide application equipment.

Allelopathy

The allelopathic potentiality of different rice genotypes against *E. crus-galli* and *C. difformis* was observed both in the greenhouse and in the field (Hassan and Rao 1994a). The rice varieties IR 1108-16-1, UPR 82-1-7, BALA and IET 1444 recorded 50 to 70% mean radial allelopathic activity against *E. crus-galli*. The allelopathic potentiality of rice should be exploited for use as a component of integrated weed management and potentially reducing the input of costly herbicides in the Near East.

FUTURE WEED MANAGEMENT RESEARCH IN THE NEAR EAST

Weed management research in rice in most of the countries in the Near East is in the budding stage. It needs to be strengthened to exploit the full potential of rice productivity in the region. Research should be accelerated on the evaluation of suitable integrated weed management practices that are consistent with other agronomic practices, as well as ways and means to enhance herbicide use efficiency to reduce the cost of weed control. Efforts must be increased to understand weed ecology in an effort to avoid undesirable shifts in weed populations as well as prevention of the development of new weed problems. Research efforts are to be intensified on development of mycoherbicides, identifying allelopathic rice cultivars and using those

innovative methods as components of integrated weed management in rice in the Near East.

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CHAPTER 11

WEED MANAGEMENT FOR RICE IN LATIN AMERICA AND THE CARIBBEAN

WEED MANAGEMENT FOR RICE IN LATIN AMERICA AND THE CARIBBEAN

A.J. Fischer and G. Antigua

INTRODUCTION

There is a wide yield gap in Latin America between the rice yields obtained by good farmers (which approach current rice yield potential) and the yields of not-so-good farmers (Ramirez *et al.* 1994). Improving crop and weed management should be the main objective in attempting to close the current gap between potential and actual rice yields. Unless this is achieved, new super yielding plant types or rice hybrids will not be able to realize their potential.

In this chapter damage caused by weeds in rice, their relationship with the different rice agroecosystems and the management implications that can be derived will be discussed. The last section deals with a prototype approach to decision making for integrated weed management in rice under the assumption that weed management not only needs to be efficient and sustainable, but also affordable and profitable.

RELEVANCE OF WEEDS IN RICE

Worldwide rice yield losses due to competition for weeds escaping control practices amount to 46 million tons, or 10% of production, each year (Ampong-Nyarko and De Datta 1991). Besides differences among countries and cropping systems, these figures clearly indicate the need for more efficient weed control in rice. According to Gonzalez *et al.* (1983), weeds are the most widespread and costly constraint for rice production in Latin American Countries (LAC). Besides competition, weeds can also affect rice quality and harvest.

Increases in Production Costs

In LAC, weed control in rice represents 20% of production costs, about 442 and 284 million US dollars in irrigated and dryland rice, respectively. Weed control (69 US dollars/ha) together with fertilisers and harvest operations are among the costliest inputs.

Hosts of Pests

Weeds can be hosts of diverse rice pests. In Venezuela (Páez *et al.* 1992) found that *Leptochloa* spp. can be host for *Spodoptera frugiperda*, while *Luziola* spp. can be host of *Lissorhoptus* sp., and *Echinochloa colona* (L.) Link can carry the Hoja Blanca Virus, *Pyricularia oryzae* Cavara and *Tagosodes* sp. Therefore keeping levees and bunds free of weeds is relevant for pest management.

Ease of Harvest and Grain Quality

Weeds can cause rice to lodge (e.g. *Sesbania exaltata* (Raf.) Cory, *Ludwigia* spp., and *Aeschynomene* spp.), or if still green at harvest they will increase the humidity of rice grain (e.g. *Ipomoea* sp.). *Ischaemum rugosum* Salisb. and *Oryza sativa* L. (red rice) are usual contaminants of rice seed. To eliminate the undesirable red pericarp of red rice seeds additional milling is required, which increases the proportion of broken grains, lowering the value of the product.

Social Costs

Small farmers spend a considerable amount of their time weeding. This not only implies a high human cost, but also limits the amount of land that they can farm. High labour costs have resulted in high herbicide usage, which poses risks to the environment and human health.

Infestations of red rice and *Rottboellia cochinchinensis* (Lour.) W. Clayton in monocropped rice fields can become unmanageable, often forcing farmers to abandon the fields.

Aquatic Weeds

Aquatic weeds (e.g. *Heteranthera limosa* (Sw.) Willd., *Eichhornia crassipes* (Martius) Solms-Laub.) are troublesome in flooded rice, blocking drains and canals and causing water losses by transpiration.

Rice-Weed Interference

Interference refers to the negative interactions among plants in a community, involving competition, allelopathy and parasitism. Understanding the factors regulating rice-weed competition is the key for developing true sustainable weed management alternatives.

There are varietal differences in competitiveness among rice cultivars, tall and late-maturing varieties tolerate weed infestations better than modern early semidwarfs (Johnson and Jones 1993; IRRI 1993). Even some varieties have shown allelopathic activity such as the inhibition of *Heteranthera limosa* by CICA 4 (Dilday *et al.* 1990). Weed interference is particularly serious in upland and lowland rain-fed crops, and whenever a permanent, weed-suppressive water film cannot be established in irrigated rice. When plants compete for the same limiting resources such as water, nutrients and light, time of occurrence and duration of weed competition are critical aspects for weed management. Weeds that emerge with the crop are most damaging (Fischer *et al.* 1993b). Inadequate water control or dryland conditions often allow for successive flushes of weed emergence. Late-emerging weeds (30 or more days after emergence) face a considerably developed crop, often affecting only yields at relatively high infestations (Figure 1); therefore the need for external inputs to control them has to be carefully examined. However late-emerging weeds can affect ease of harvest, storage and quality of the harvested grain.

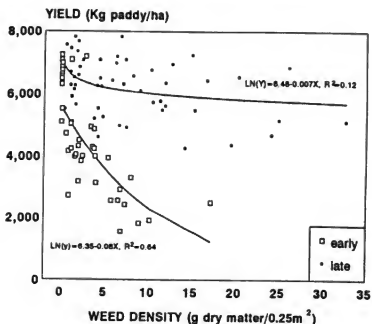


Figure 1. Effect of weed densities on rice, when weeds emerged a) with the crop (early) or b) 30 days after (late). A.J. Fischer, 1994 (unpublished).

Increasing rice seeding density can be an effective way to suppress weeds, especially late-emerging ones (Figure 2). However, lodging and diseases can set limits to increasing rice populations. Rice is more competitive with an associated species when seeded at close spacing (Figure 3).

When a weedy field is fertilised, weed growth is stimulated and the benefit of the added nutrient can disappear (Ampong-Nyarko and De Datta 1991). Competition for light occurs in an irrigated and well fertilised crop. Tall, leafy and droopy-leaved rice plants tend to be more competitive for light (Jennings and Herrera 1968). One of the reasons for *Rottboellia cochinchinensis*' competitiveness is its rapid initial growth overtopping rice. In upland and lowland rain-fed rice, competition for water is usually a concern. Rice is most affected when the moisture stress occurs at or near flowering. Growth reduction and leaf rolling are symptoms of moisture stress.

Deep rooted plants or those with roots capable of growth to search for moisture as the soil profile dries, should have a comparative advantage under water-limiting conditions. Such characteristics can be seen in some upland cultivars such as the Brazilian IAC 165 (Figure 4). Deep rooting was also stronger for the upland cultivar when growing under below-ground competition with *Echinochloa colona*, when water was not limiting (Figure 5). Under such conditions IAC 165 was more competitive than the irrigated cultivar (data not shown).

RICE AGROECOSYSTEMS AND IMPLICATIONS FOR WEED MANAGEMENT.

Rice in LAC is grown in various ways and environments, thus weed problems and opportunities to manage them differ with each agroecosystem. The most relevant variables are the availability and control of water, land levelling and preparation, as well as sowing method.

Irrigated Rice

In LAC 2.5 million hectares of rice are grown under irrigation, this amounts to 34% of the area seeded to rice. Irrigated rice accounts for 60% of LAC rice production. In this system the use of weed control inputs can be very high. Four variations of the irrigated rice system will be discussed.

Transplanted rice. This system is the least common in LAC, and is only found in certain areas of Peru (Pacific Coast), Ecuador, and Colombia.

Twenty- to 30-day-old rice seedlings are transplanted from nurseries into puddled flooded soil. Puddling (land preparation and levelling in flooded conditions) is accomplished with diverse motorised or animal-drawn implements to achieve complete soil disaggregation, after which soils are levelled. Two to six rice seedlings are planted in hills 15 to 25 cm apart (Tascón 1985), closer planting improves rice competitiveness against weeds but lodging and pests can become a problem. Seeding in parallel rows facilitates mechanical weed control.

Water-loving weeds tend to proliferate with a continuous rice monocrop. Some of the weeds that appear in this system are: *Echinochloa crus-galli* (L.) P. Beauv., *E. colona*, *Cyperus difformis* L., *Cyperus iria* L., *Fimbristylis* spp, *Heteranthera limosa*, *Heteranthera reniformis* Ruiz et Pav. and *Limncharis flava* (L.) Buchenau. Weed control must start in the nurseries to avoid transplanting rice mimic weeds. Good water control maintains anaerobic conditions in the soil to inhibit growth of most non-aquatic weeds. Soil puddling uproots and buries existing vegetation and weed seeds, most buried weed seeds cannot germinate in anaerobiosis.

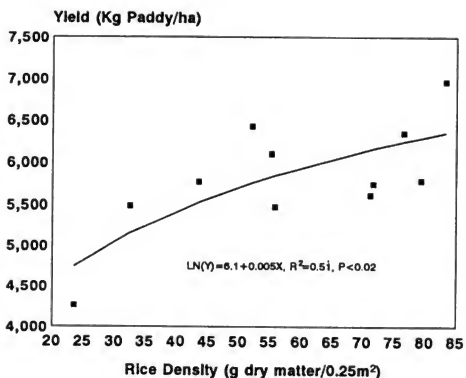


Figure 2. Rice yield as affected by increasing rice densities (expressed as rice foliar biomass), for a weed infestation of 10 to 16g weed dry matter/0.25m².

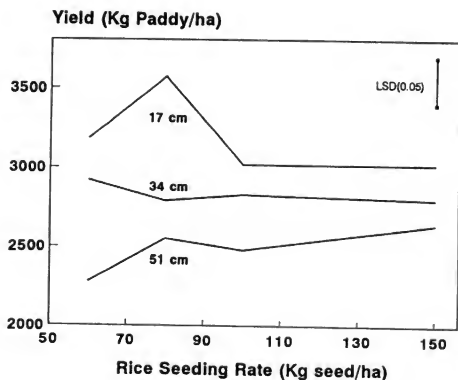


Figure 3. Yields of upland rice intercropped with *Brachiaria dictyoneura*, at three row spacings: 17, 34, and 51 cm. A.J. Fischer, 1992 (unpublished).

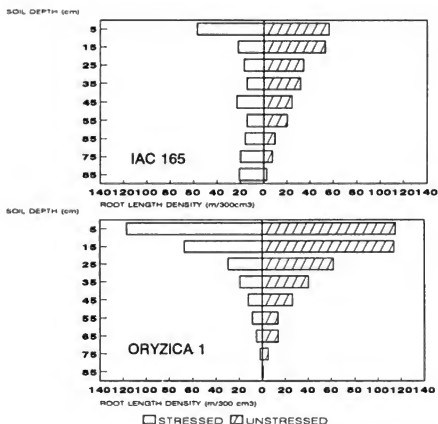


Figure 4. Root growth of an upland (IAC 165) and an irrigated (Oryzica 1) rice cultivar, as affected by moisture stress and a receding water table. (A.J. Fischer and H.V. Ramirez, 1992 unpublished).

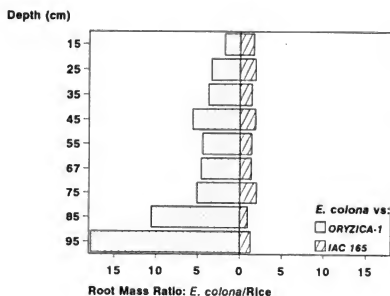


Figure 5. Rooting patterns of an upland (IAC 165) and an irrigated (Oryzica 1) rice cultivar when each grew under below-ground with competition *Echinochloa colona*, with no moisture limitation. (A.J. Fischer and H.V. Ramirez, 1992 unpublished).

Puddling has been the key to suppress red rice infestations. Transplanted rice seedlings have a competitive advantage over the small emerging weeds, however, it is important to establish and maintain a permanent flood water film as soon as possible. The crop should grow weed-free for about six weeks after transplanting (Ampong-Nyarko and De Datta 1991). Herbicides are used in this system together with manual and mechanised (small equipment) weed removal.

Direct seeding on saturated soil. This system is widely adopted in LAC, especially in southern Brazil, Chile, Venezuela, Cuba, some Caribbean countries and in some places of Colombia. The seedbed is prepared and levelled under wet (puddled) conditions. Good levelling is essential for water control. Rice seeds are pre-germinated and broadcast after draining the field, which avoids oxygen depletion in standing water due to the high summer temperatures, which can kill or greatly reduce rice seedlings' growth. Levelling is important for uniform flooding, and to minimise the area with puddles after draining. In the puddles, growth of rice seedlings will be hampered by anoxia and weeds will later proliferate until a permanent flood can be established. Moderate to high rice tillering ability is desirable to compensate for such stand reductions and often also high seeding rates (>150 kg/ha) are employed. In Chile and some areas of Brazil (State of Sta. Catarina), lower water temperatures allow the broadcast of pre-germinated seed into flooding water, this should reduce the risks of weeds emerging with the crop and save water, since draining after seeding is not necessary. However, genotypes capable of emerging through a water film under tropical temperatures exist (Yamaguchi *et al.* 1993) and are used in certain areas of Latin America, such as Surinam, indicating the potential for the introduction of such characteristics into modern varieties to lower weed control costs and reduce herbicide use.

After the water is drained the rice seedlings anchor in the mud and grow in height. As they grow, flooding can be gradually restored (usually as from 20-30 days after emergence). This management allows for weed establishment and growth before a permanent flooding film of water can be established, and usually demands the use of herbicides. Good levelling and water control are key factors for weed management in this system, where some of the relevant weed species are: *Heteranthura limosa*, *H. reniformis*, *Limnocharis flava*, *Ludwigia* spp., *Oryza sativa* (red rice), *Echinochloa colona*, *E. crus-galli*, *Ischaemum rugosum*, *Cyperus iria*, *C. esculentus* L., *C. difformis*, *Fimbristylis annua* (L.) M. Vahl, *F. littoralis* Gaudich., *Luziola subintegra*, *L. brasiliensis*, *Leptochloa* spp., *Eleocharis* spp., *Sagittaria guayanensis* H.B.K., *Aeschynomene* spp., *Sesbania exaltata*, *Sphenoclea zeylanica* Gaertner (González *et al.* 1983; Pérez *et al.* 1992; Arias *et al.* 1991; Herrera *et al.* 1991; García *et al.* 1992). Aquatic and semi-aquatic weeds tend to prevail with continued rice monocrop under this system. Tables 1 and 2 present options for chemical control for this system in Brazil. Three aspects are relevant for weed management: a) puddling with the anaerobiosis that inhibits weed germination, b) growth advantage over weeds due to pre-germination, and c) flooding that prevents successive flushes of weed emergence during the season. Often, to avoid excessive weed growth before flooding, fertilising is delayed until effective flooding can be accomplished. If rice is continuously farmed under this system aquatic weeds can become a serious problem. In deep heavy soils, continuous puddling can result in problems at harvest time where heavy combines often sink. Alternate dry and wet seeding or, when feasible, rotations with upland crops is recommended.

Direct seeding on a dry seedbed. This is the most popular system in LAC where there are two variants, a) one with good land levelling and flood irrigation, and b) another with contour bunds and poor or no land levelling, where irrigation flows in a succession of flushes from the higher elevations. This latter system, mostly seen in the high-yielding rice areas of Colombia, results

Table 1. Response of relevant weeds to the application of herbicides used in irrigated rice sown with pre-germinated seed.¹

Weeds	propanil	molinate	quin- clorac	oxadiazon	thiobencarb	oxyfluorfen	2,4 D	fenoxaprop- ethyl	propanil + molinate	propanil + thiobencarb	propanil + 2,4 D	ben- tazon
<i>Echinochloa</i> spp.	C ²	C	C	C(b)	C	C(b)	NC	C	C	C	C	NC
<i>Fimbristylis</i> sp	C(a)	C	NC	C(b)	C	C(b)	C	NC	C(a)	C(a)	C	C(a)
<i>Heteranthura</i> sp	C(a)	NC	NC	NC	M	NC	C	NC	C(a)	C(a)	C	C(a)
<i>Ischaemum</i> sp	C	C	ni	ni	ni	ni	NC	C	C	ni	ni	NC
<i>Oryza sativa</i> L.	NC	NC	NC	C(b)	M(b)	C(b)	NC	NC	NC	NC	NC	NC
<i>Sagittaria montevicensis</i>	NC	NC	NC	NC	NC	NC	C	NC	NC	NC	ni	C(a)
<i>Sagittaria guianensis</i>	C(a)	NC	NC	NC	M	NC	C	NC	C(a)	C(a)	C	C(a)

¹ Source: EPAGRI 1992.

² Abbreviations: C= more than 80% control; M= moderate control (60-80%); NC= no control; ni= no information; a= control obtained with weeds at the seedling stage; b= control obtained with pre-sowing applications to the flood water.

Table 2. Some herbicide treatments suggested for irrigated rice direct seeded with pre-germinated seed.¹

Common name of herbicide	Rate (kg ai/ha)	Time of application
Propanil ²	2.2-3.6	POST ³
Molinate	3.0	POST
Oxadiazon	0.55	PRE
Thiobencarb	3.0-4.0	PRE/POST
Oxyfluorfen	0.24	PRE
Bentazon	0.7-1.0	POST
2,4-D amine	0.36-1.0	POST
Fenoxapron-ethyl	0.06-0.1	POST

¹ Adapted from: EPAGRI 1992.

² Can be mixed with: molinate, pendimethalin, butachlor, thiobencarb, and 2,4-D.

³ Abbreviations: PRE, pre-emergent; POST, post-emergent.

from difficulties in levelling the slopy land (slopes>5%). Also, poor water availability often does not allow for permanent flooding even if the land can be levelled. Thus irrigation is often intermittently applied (flush irrigation), and the first flood is usually delayed (30-45 days after sowing) until rice is tall enough to compensate for terrain unevenness. Rice seed is broadcast or drilled into a dry seedbed. Broadcast seed is usually covered with a rather heavy disc harrow which buries much of the seed too deeply. To compensate for the subsequent stand reduction and to minimise weed competition, farmers usually employ high sowing rates (>150 kg/ha). Drill sowing provides a more uniform stand and usually allows the use of less seed (EMBRAPA and CNPAF 1994).

Sowing on a dry seedbed helps reduce water-loving weed species' populations that develop after continuous rice monocrops on puddled soil. However, with dry sowing, weeds are a more serious problem than when pre-germinated seed is used, since there is no puddling (anaerobiosis) and rice has no growth advantage over the weeds (as is the case when pre-germinated seed is used). Ideally, permanent flooding should be established about four weeks after sowing. With intermit-tent irrigation (poor water control or availability) this is not possible, and several weed cohorts emerge to compete with the crop. Yield losses can be serious and have prompted farmers to spray herbicides up to four times during the season (Fischer and Ramirez 1993b). The repeated use of propanil in Colombia has resulted in the proliferation of *Echinochloa colona* biotypes that are resistant to this herbicide, forcing farmers to use other, more expensive herbicides (Fischer *et al.* 1993a). When irrigation flows from the high fields, rice germination is uneven, and nutrients tend to accumulate in the low areas where weeds usually are more developed, making timely and selective herbicide applications over the whole area difficult. Weeds are similar to those in the pre-germinated system although aquatics are not so important. Some of the species reported in this system include: *Oryza sativa* (red rice), *Echinochloa crus-galli*, *E. colona*, *Sesbania exaltata*, *Paspalum* spp., *Digitaria sanguinalis* (L.) Scop., *Rottboellia cochinchinensis*, *Eleusine indica* (L.) Gaertner, *Leptochloa* spp., *Phaseolus latyroides*, *Stenotaphrum secundatum*, *Cyperus rotundus*, *C. iria*, *C. ferax*, *Fimbristylis annua*, *Murdannia nudiflora*, *Commelina diffusa*, *Ipomoea* spp., *Eclipta alba* and *Cassia tora* L. (González *et al.* 1983; Páez *et al.* 1992; Arias *et al.* 1991; Herrera *et al.* 1991; García *et al.* 1992).

Land levelling and water control allowing for permanent flooding are the pillars for weed control in irrigated rice. Crop rotations have been useful, especially with heavy red rice infestations which can be controlled selectively with herbicides in other dryland crops (sorghum, soybeans, cotton). However, it is not always possible to grow other crops in many of the low and poorly drained rice fields, thus chemical control prevails. Herbicide recommendations for weed control in direct-seeded rice in Brazil are presented in Tables 3 and 4. Mechanical hoeing is popular in southern Brazil when rice is drilled in rows, manual roguing is often employed to remove mature red rice plants and panicles before they shatter seed.

Reduced and no-till practices have become popular in the southern continent. In southern Brazil, an annual pasture is planted in autumn, providing forage during winter and suppressing weed growth. In spring the vegetation is desiccated with a herbicide, and rice is sown with a no-till planter. This system has been particularly successful to recover red rice-infested fields. No-till appears to work well in levelled fields, and can also include some light tillage (EPAGRI 1992).

Rain-fed and Upland Rice

In LAC 4.6 million ha of dryland rice are grown, 84% in Brazil and the rest is mostly in Central America, Colombia, Ecuador, and Venezuela. Rain-fed rice accounts for 40% of the rice produced in the region. Rain is the source of water, and since there is no puddling nor permanent flooding, weeds become a very serious problem. Weeds emerge with the crop and in successive flushes thereafter. Since water is limited, plants should compete for water earlier than in irrigated systems, also initial rice growth is slower than when pre-germinated seed is used. Dryland rice is found in the acid, low-fertile, well-drained soils of the savannas, as well as in the flood-prone lowlands of Central America and Brazil. Water availability varies from areas with abundant rainfall to areas where rainfall is erratic, resulting in periods of moisture stress or drought. Two variants of this system can be distinguished.

Lowland rain-fed rice. This system is very common in Central America, and no bunds are used. At the onset of rains rice seed is drilled or broadcast on a dry seedbed. Sowing densities exceed 100 kg/ha to withstand weed competition and to compensate for stand losses due to uneven seed coverage. Later, in low areas, the water table will be close to rice roots or even flooding of variable duration may occur.

Some representative weeds of this system are: *Echinochloa crus-galli*, *Ischaemum rugosum*, *Leptochloa* spp., *Cyperus difformis*, and *Fimbristylis* spp (González *et al.* 1983; Páez *et al.* 1992; Arias *et al.* 1991; Herrera *et al.* 1991; García *et al.* 1992). Red rice is a weed of dryland rice in seven countries (González *et al.* 1983). Where fields become frequently waterlogged or flooded, water-loving species may prevail. Competition usually starts early in the season, thus weed control generally involves pre-emergent herbicides. Such herbicides should be applied on moist soil or under the certainty of immediate rain, otherwise weed control becomes erratic. One weeding operation or herbicide application will hardly be enough given the successive flushes of weed emergence that usually occur. Rice cultivars for this system should be competitive and deep rooted to withstand periods of moisture stress. Crop rotations can be useful to manage weeds (red rice), their use will depend on soil drainage.

Upland rice. This is grown usually on moderately to well drained soils, with variable fertility and relatively low cation exchange capacity. Rainfall is more or less erratic to abundant, as in the favourable upland savannas of Colombia, Venezuela, and Guyana. Soil acidity, with

Table 3. Response of relevant weeds to the application of herbicides used in irrigated rice direct-seeded on a dry seedbed.¹

Weeds	'propa- all	moll ate	quin chlorac	pendim thalin	buta chlor	oxadiaz on	thiofen carb	oxyflu- orfen	2,4 D	fenoxa prop- ethyl	propaill + molinate	propaill + pendim thalin	propaill + thiofen carb	propaill + 2,4 D	propaill + oxadiazon	benazox a
<i>Aschynomene</i> sp	M(a) ²	NC	C	NC	NC	NC	NC	NC	C	NC	M(a)	M(a)	M(a)	C	ni	NC
<i>Brachiaria</i> spp.	C	C	NC	C	C	C	C	C	NC	C	C	C	C	C	C	NC
<i>Cyperus</i> spp.	M(a)	C(b)	ni	NC	ni	NC	ni	ni	ni	NC	C(a)	M(a)	M(a)	C	M(a)	C(a)
<i>Digitaria</i> spp.	C	C	NC	C	C	C	C	C	NC	C	C	C	C	C	C	NC
<i>Echinochloa</i> spp.	C	C	C	C	C	C	C	C	NC	C	C	C	C	C	C	NC
<i>Fimbristylis</i> sp.	C(a)	C	NC	ni	ni	ni	ni	ni	C	NC	C	ni	C(a)	C	M(a)	C(a)
<i>Ischaemum</i> sp	C	C	ni	ni	ni	ni	ni	ni	NC	C	C	ni	C	ni	ni	NC
<i>Oryza sativa</i> L.	NC	M(c)	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC	NC

¹ Source: EPRAGI 1992.

² Abbreviations: C= more than 80% control; M= moderate control (60-80%); NC= no control; ni= no information; a= control obtained with weeds at the seedling stage; b= control obtained with pre-plant incorporated applications, or with early post-emergent treatments; c= control obtained with a rate 30% higher than usual with a pre-plant incorporated treatment applied at least 10 days before seeding.

Table 4. Some herbicide treatments suggested for broadcast or drill-seeded irrigated rice sown on a dry seedbed.¹

Common name of herbicide	Rate (kg ai/ha)	Time of application
Propanil ²	3.0-5.0	POST ³
Molinate	4.0	PPI/POST
Quinclorac	0.38	POST
Pendimethalin	1.3-1.8	PRE
Butachlor	2.4-3.6	PRE
Oxadiazon	0.75-1.25	PRE/POST (early)
Thiobencarb	3.0-4.0	PRE/POST
Oxyfluorfen	0.24	PRE
Bentazon	0.7-1.0	POST
2,4-D amine	0.36-0.5	POST
2,4-D ester	0.24-0.5	POST
Fenoxaprop-ethyl	0.10-0.20	POST

¹ Adapted from: EPAGRI 1992.

² Can be mixed with molinate, pendimethalin, butachlor and 2,4-D.

³ Abbreviations: PRE, pre-emergent; POST, post-emergent; PPI, pre-plant incorporated.

high aluminium saturation and deficiencies of iron, zinc, calcium and magnesium frequently occurs. Phosphorus is usually deficient in oxisoils and ultisoils and potassium may be scarce in coarse-textured soils exposed to abundant rain. Thus rice germplasm adapted to this particular environment is required. This system can be present under diverse management conditions, from itinerant slash and burn farmers on the forest margins to the large, mechanised, farms of the cerrados and the savannas. Tillage is essential to reduce weed pressure before seeding, with regular rainfall the stale seedbed may be a useful technique; rice seed is mostly drilled. Given the moisture limitation, rows can be spaced up to 30 cm and sowing rates are lower (about 70 to 80 kg/ha) than with irrigated rice. Seeding densities tend to be increased when rice is broadcast. Cultivars required for this system have to be competitive, deep-rooted, intermediate height and tillering and eventually be tolerant to diseases and soil acidity.

Weeds after the second or third year of monocropped rice are the most serious problem of upland rice. Competition starts early in the season given that water and soil resources are limited. Weeds emerge with the crop and continue to emerge during the growing season until rice canopies completely shade the ground. C-4 weeds such as *Echinochloa* spp. should have advantage over rice (C-3) in this hot environment where moisture stress can occur. Some of the more common weed species are: *Echinochloa* spp., *Rottboellia cochinchinensis*, *Ischaemum rugosum*, *Digitaria sanguinalis*, *Leptochloa* spp., *Cyperus rotundus* L., *C. iria*, *Cyperus ferox* Rich., *Ipomoea* sp. and *Amaranthus* spp. (González *et al.* 1983; Pérez *et al.* 1992; Arias *et al.* 1991; Herrera *et al.* 1991; García *et al.* 1992). Tillage prior to seeding is important to reduce early weed pressure, and an even stand will allow for uniform ground shading to inhibit weed growth. The crop needs to be weeded from emergence until rice canopies completely cover the ground. Mechanical weeding is possible if rice has been seeded in rows. Rotations with other crops (sorghum, pastures, soybeans, beans, and corn) are usually possible and recommended (though adapted cultivars are required for areas with acid soils) not only to reduce weed populations, but also for the conservation of the resource base. Chemical control is also an

option. In Brazil, in the states of Goiania, Rondonia, Mato Grosso and Maranhao, the following species are common weeds of upland rice: *Acanthospermum* sp., *Ageratum conyzoides* L., *Amaranthus* sp., *Bidens pilosa* L., *Cassia tora*, *Ipomoea* sp., *Sida* sp., *Cyperus* sp. and grasses such as *Cenchrus echinatus* L., *Digitaria* sp., *Eleusine indica* and *Brachiaria plantaginea* (Link) Hitchc. (EMBRAPA-CNPAP 1994). Herbicides recommended for such weeds appear in Table 5. Other chemical options available include bentazon post-emergent for broadleaf weeds, pyrazosulfuron-ethyl appears promising against sedges, oxyfluorfen and butachlor can be used pre-emergent against broadleaf weeds and grasses (some injury to rice can appear with oxyfluorfen). Weed management alternatives still need to be developed for the rice-pasture intercropping system in the cerrados and the savannas.

Table 5. Herbicides for weed control in upland rice in Brazil¹.

Common name of herbicide	Rate (kg ai/ha)	Time of application ²
Pendimethalin	1.25-1.5	PRE
Oxadiazon	0.75-1.0	PRE
Bifenox	10.0	PRE
Propanil	3.6-4.3	POST
Thiobencarb + propanil	3.2 + 1.6	POST
Propanil + 2,4-D	3.8 + 0.72	POST

¹. Adapted from: L.F. Stone, 1994.

². PRE= pre-emergent, POST= post-emergent.

RED RICE

Red rice is a serious weed where rice is grown (Baker and Sonnier 1983), particularly in the irrigated, direct-seeded areas of the Americas (Gonzalez 1985; Smith 1991; Antigua 1985). There is some confusion in the taxonomy of this weed, for some authors it is *Oryza sativa* L., while others consider it to be *O. rufipogon* Griff, *O. punctata* Kutschy ex Stend, *O. barthii* Chev. or *O. longistaminata* Chev, Roehr. (Tateoka 1963; Parker and Dean 1976; Wirjahardja *et al.* 1983; Baker and Sonnier 1983). As many as seven *Oryza* species have been listed as weeds (Holm *et al.* 1979).

Red rice is a common contaminant of rice seed. Its common name results from the red aleurone pericarp which is undesirable commercially. The colour of the pericarp is controlled by one pair of genes, with red being dominant (Grist 1975); however, other complementary genes may be involved (Gonzalez 1985). The intense milling required to remove its pigmented aleurone layer (bran) results in a high proportion of broken grains which lowers head rice yields (Smith 1992; Gonzalez 1985). Besides its effects on grain quality, red rice can be a very competitive weed since it is usually taller and more tillered than rice (although considerable morphological variability exists). According to Baker and Sonnier (1983) the value of yield losses caused by red rice competition far outweigh the value of quality losses. Other weedy features are its early maturity, shattering before rice harvest and prolonged dormancy, which ensures reinfestations. Red rice is a common contaminant of rice seed and its morpho-physiological similarity to rice makes its selective removal with herbicides almost impossible. According to Smith (1988), 3 to 19 red rice plants per m² resulted in 10 to 50% rice yield reductions, respectively. Late cultivars, such as Mars, were more competitive against red rice than earlier ones like Lebonnet

(Diarra *et al.* 1985), and taller varieties (Lebonnet) were more competitive than modern semidwarfs (Kawano *et al.* 1974; Smith 1992). In southern Brazil, De Souza (1989) found that approximately 60 red rice plants per m² reduced rice yields by about 50%. In Cuba, rice yields can be reduced by 90% with red rice populations with 286 panicles/m². In Colombia, season-long interference by 5 to 20 red rice plants per m² lowered rice yields by about 40 to 60%, while 24 plants per m² competing only during the first 40 days of the growing season reduced yields by 50% (Fischer and Ramirez 1993a). Diverse red rice morphologies as a result of cross fertilisation have been found (Montealegre and Vargas 1992). Cross fertilisation can even occur with cultivated rice (Perez *et al.* 1973; Galli 1992). Morphological diversity of red rice has been associated with differences in competitiveness (Fischer and Ramirez 1993a). Thus, such polymorphism in red rice populations (Galli 1992) complicates the prediction of rice yield losses resulting from red rice competition.

There are diverse strategies for red rice control available in LAC, which reflect the diversity of rice agroecosystems and socioeconomic conditions in the continent. To avoid herbicide abuse, it is of utmost importance that **preventive** measures be taken. The most relevant of which is the use of red-rice-free seed. In most countries some red rice contamination is allowed in certified seed, this ensures the permanent reinfestation of rice fields. There is often a lack of financial incentive for farmers to use certified seed, resulting in interchange of contaminated seed with other farmers, or returning (contaminated) seed from one year to the next. Machinery and equipment should be cleaned when moving out of infested fields and irrigation water coming from infested fields should not be used. In addition, commercial aeroplane sowing should not be closer than 200 m from fields intended for quality seed production.

Among **cultural** practices, tillage should be used to encourage the emergence of red rice seedlings for their elimination. However, tillage should be shallow so as not to store this long-dormancy-prone seed in the soil. In some cases delaying the first tillage after harvest leaves red rice seed exposed to temperature extremes and to the action of birds and mice. Anaerobiosis by flooding prevents red rice germination. Puddling and transplanting into flooded fields has been a very successful practice, which has allowed many severely infested fields where rice could no longer be grown to return to use. A successful approach in direct-seeded rice has been to prepare and flood the soil and then, after seeding, leave a very thin film of water just enough to maintain anaerobiosis in the soil. Then as the rice seedlings grow, flooding is resumed gradually. Armenta and Coulombe (1993) report good red rice suppression when the fields were left flooded after puddling for 20 days, then drained and seeded to finally resume gradual flooding 5 to 10 days after seeding. For such techniques to be effective good land levelling and water control are required. Sowing rice through the water of flooded fields prevents red rice infestation, however it can reduce rice stands significantly (Baker *et al.* 1986). Germplasm suitable for direct sowing under flooded conditions has been reported by Yamaguchi *et al.* (1993); research on this topic is also being conducted in LAC. Increased rice densities and pre-germinated seed have improved the ability of rice to compete with this weed (Sonnier 1978). However, continued rice monocropping will inevitably lead to red rice infestation (Smith 1992). Rotation with other crops besides modifying the habitat, allows for the use of herbicides that cannot be employed selectively in rice. Crop rotations have been successful, but lower market prices for alternative crops and drainage problems (Galli 1992) usually discourage farmers from this practice. In Rio Grande do Sul, Brazil, a successful practice has been developed (EPAGRI 1992) whereby an annual pasture (usually *Lolium multiflorum* Lam.) is grown for cattle grazing during winter and to prevent red rice from establishing in the early spring. Shortly before planting, the *Lolium* sward is killed with a non selective herbicide application and rice is then

direct seeded in the sod.

When rice is seeded in rows, red rice plants can be easily distinguished and removed by hand or **mechanical** means. Otherwise, hand weeding must be delayed until about 30 to 60 days after rice emergence before red rice plants become sufficiently taller and distinguishable from rice. Reinfestations are prevented in Colombia (Valle del Cauca) to a certain extent by hand pulling immature red rice panicles or cutting with machete. However the cut plants can still produce new shoots and more seedheads. Mechanical cultivation and hoeing can be useful in row-seeded crops. Armenta and Coulombe (1993) reported a 40% red rice reduction using a manual rotary hoe 23 days after sowing rice. Eliminating red rice seeds in the milling process is tedious and leads to rice losses. However, some millers in southern Brazil utilise large numbers of electronic units that can colorimetrically detect the darker red rice seeds and blow them away from the commercial seed with a jet of air; certainly an expensive operation.

In terms of **chemical control**, the stale seedbed is one of the more widely adopted practices in irrigated rice whereby red rice is encouraged to germinate by flushes of irrigation or for 12 or 15 days, and then when it reaches a state of development between seedling and tillering is sprayed with glyphosate or oxyfluorfen; finally rice is seeded with pre-germinated or dry seed (Montealegre and Vargas 1992). Seventy percent of the red-rice-infested area in Colombia is treated in this way (Montealegre and Vargas 1992). The use of rope-wick applicators is becoming popular for treating of weed patches. Wicks soaked with a glyphosate solution "comb" the red rice plants when these become taller than rice. This principle has also been utilised in Cuba for hand roguing. The use of molinate as a pre-plant incorporated application has been an effective alternative. Biotechnological techniques have allowed for the transformation of rice plants with genes for resistance to certain non-selective herbicides that could control red rice (Linscombe *et al.* 1994). In Cuba, hybridisation programs have attempted to introduce resistance to glyphosate rice and to the grass herbicide alachlor. However, the success of these techniques is in jeopardy since such resistance to specific herbicides can also be present in certain red rice genotypes (Noldin *et al.* 1994), or can be transferred to rice by natural crossing (Galli 1992).

Economic analyses using competition data demonstrated that in Colombia, chemical red rice control still tended to be cheaper than alternatives, such as hand weeding (Fischer and Ramírez 1993a). This suggests that in a continuous rice monocrop, if red rice management is restricted to field control measures (as opposed to an integration with preventive measures or rotations), dependence on herbicides use may be continued.

INTEGRATION OF ALTERNATIVES FOR WEED MANAGEMENT

Integrated weed management (IWM) implies the combination of vegetation management strategies, so that losses caused by weeds can be minimised economically and any negative environmental effects are minimised. The concept of diversification is implied; we have mentioned briefly how the repeated use of the same weed control method was, in the long term, not sustainable. In some areas of Colombia, the misuse of herbicides, such as the repeated use of propanil on the same rice fields, caused a buildup of resistance to this herbicide in populations of *Echinochloa colona* (Fischer *et al.* 1993a) or *E. crus-galli* (Carey *et al.* 1992). Also, the continuous use of puddling and flood irrigation usually leads to weed population shifts where aquatic weeds become a problem, requiring a change in weed control methods. The continuous irrigated rice monocrop has led to widespread infestations of red rice throughout the continent. Severely infested fields often become unsuitable for rice production and are abandoned.

Alternatively, diversification through crop rotations, besides helping to manage weeds, is usually associated with soil conservation, nutrient cycling, and pest management. Thus diversification and integration of crop and weed management alternatives, relate to the sustainability of a cropping system.

Defining economic criteria for selecting and integrating crop and weed management options in IWM programs is fundamental for the adoption and implementation of such programs. Awareness of the risk of yield losses by weed competition is typically inaccurate among farmers; after all, farmers do not have weed-free checks in their fields. The basic concept is that when a farmer can predict how much money he will lose from a given weed infestation, he will then be able to decide how much he can afford to spend in controlling those weeds.

To achieve the above-mentioned economic risk awareness at farmer level, a two step approach is proposed:

- 1) Studies to predict losses by weed competition (just for simplicity we will consider here only yield losses, but other kinds of crop losses may eventually have to be considered also).
- 2) Estimation of gross margins (value of the benefit to be obtained) minus the cost of management strategy.

We will discuss here two examples to illustrate how competition studies can be used to estimate yield losses to weeds and to assist in the selection of weed management alternatives. The first example is on red rice as a weed of flush (intermittent) irrigated rice in the Cauca Valley of Colombia, near the International Center for Tropical Agriculture (CIAT).

The relative benefit of controlling red rice in the field depends on two main aspects, a) the density of the weed (plants or stems per m²), and b) the time of red rice removal (duration of the competition). From field experiments, a function relating rice yield loss to red rice density and to the duration of red rice competition was obtained (Figure 6). Using the model in that figure, rice yield losses could be predicted and the gross margins of two management strategies, namely pre-emergent chemical control (for which a red rice density has to be anticipated before it emerges) and post-emergent hand removal 35 days after rice emergence, were estimated. In this specific example, chemical control was the most profitable alternative. In the same way, other alternatives can be proposed and selected for integration in a management program.

In some of the high-yielding rice producing areas of Colombia, fields cannot be permanently flooded due to poor water control and slopy topography. Under such conditions, well irrigated weeds can emerge in successive flushes during the growing season and force farmers to spray herbicides three to four times per season. The cost of weed control is thus very high and the environmental implications may be considerable given the continuous flow of irrigation water through the rice fields. The repeated use of propanil in this system has led to the buildup of propanil-resistant biotypes of *Echinochloa colona* (Fischer *et al.* 1993a). At this point it is clear that farmers in this system need clear criteria or decision rules for selecting weed management options to integrate in a program seeking lower costs and rational herbicide use. Such decision rules can be derived from competition studies to predict yield losses caused by weed infestations consisting of mixtures of diverse species which appear at different densities. As we stated

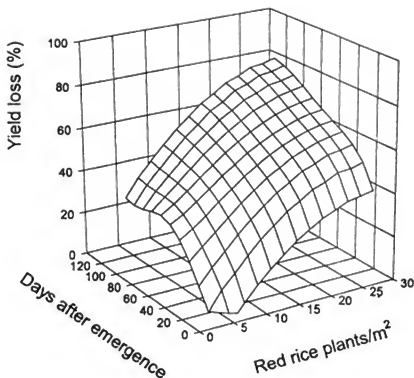


Figure 6. Rice yield losses when rice grew for different periods with a range of red rice (*Oryza sativa*) densities; where: $\text{Yield loss (\%)} = 169 - 4.73 \times \text{DENSITY} + 0.082 \times \text{DENSITY}^2 - 16.66 \times \text{XLN}(\text{PERIOD} + 1)$, $R^2 = 0.86$, $P < 0.0009$.

Adapted from Fischer, A. 1991. Manejo integrado de malezas: implicaciones ambientales, prediccion de perdidas, agronomia y plagas. pp. 9-22 in J.L. Armenta Soto and M. Castillo, eds. Mesa Redonda sobre Proteccion Vegetal. Red de Mejoramiento de Arroz para el Caribe. Santa Clara, Cuba.

before, if the economic losses can be predicted, then there is a basis to decide how much can be spent to avoid such losses. A basis for choosing among different alternatives for weed management can be the use of gross margins estimated using yield loss-weed density relationships. Competition studies with multi-species weed infestations were conducted at CIAT, and to derive a predictive model relating yield losses to levels of weed infestation, the approach of Wilkerson *et al.* (1991) was followed. We worked with natural infestations of four weed species, and each weed grew independently (unwanted species were hand removed) at a range of densities (plants/m²) with rice. Thus four density series were obtained. Linearising the yield loss relationships, four linear regressions were obtained (Figure 7a). For each species the slope (regression coefficient) of the regression estimated the competitiveness of each species with rice. If each species' density was weighted by the value of its slope divided by the value of the largest slope (that of the most competitive species), all densities could be expressed in relative terms, or as equivalent densities with respect to the most competitive weed species. For a given weed infestation in the field, the addition of the respective equivalent densities for all species present would represent the total weed density (expressed in relative or equivalent terms) that the crop has to compete with. Thus if the yield loss relationships were expressed in terms of the total equivalent density, a single function would result (Figure 7b). A more accurate procedure, if software for non-linear regression is available, would be to fit a more biologically interpretive model to the data, such as the rectangular hyperbola proposed by Cousens (1986). Even more elaborate analyses also account for weed-weed interference in estimating relative competitiveness (Stinton *et al.* 1994). Such functions allow prediction of rice yield losses from mixed-species weed infestations and to estimate the gross margins of different weed management alternatives. Table 6 illustrates how this approach can be used to select weed

control options. In this example, the use of herbicides was economically justified (gross margin >0) for weed infestations higher than 13 *equivalent* plants/m² (which in this case was equal to 13 plants of *Echinochloa colona*/m²), whereas hand weeding was economic at somewhat higher densities of weed infestation.

When yield loss predictions are used to derive economic thresholds to decide whether to apply control or not, a word of caution is necessary. If the gross margin of a certain strategy is negative, the most economic alternative may be not to control weeds at all. In this case the weeds that are allowed to stay in the field will produce seed that will enrich the soil seed bank. After some time of following this approach, the weed populations in that field may have increased as a result of such replenishment of the weed seed reservoir in the soil. Thus future weed control costs would be increased. If such problems can be predicted, the economic thresholds may have to be lowered accordingly (i.e. control weeds at densities lower than the threshold). Such adjustment is achieved by conducting economic analysis on a range of possible thresholds.

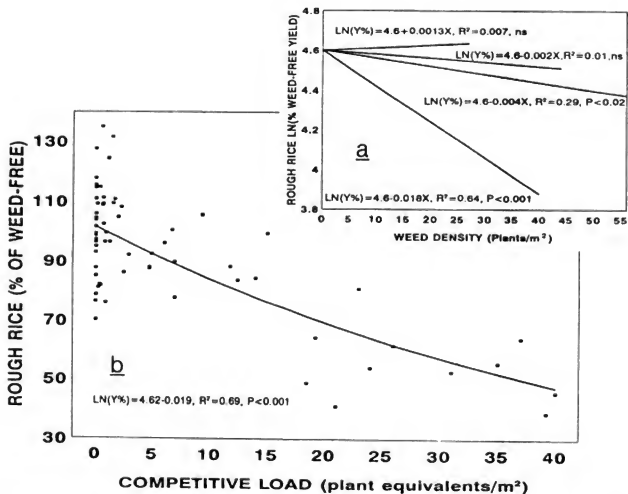


Figure 7. a) Relative competitiveness of four annual weeds with rice. b) Predictable rice yields losses resulting from the total competitive load imposed by these four weeds, growing at various densities in mixed stands with rice. Modified from Fischer, A.J. 1992. CEIBA 33(1): 272-289.

Table 6. Cost/benefit analysis using a crop loss function derived from competition studies, and two weed management alternatives.

	Herbicide	Handweeding
Total competitive load (plants/m ²)	13	19.2
Predicted yield loss ¹ (Kg/ha)	214	300
Gross margin (\$US) ²	0	0

¹ From the equation: $LN(Y) = 4.6 - 0.0026X$, $R^2 = 0.47$, $p < 0.001$, where Y = yield loss as percent of weed-free yields (estimated at 5600 kg/ha), and X = total competitive load in plants/m².

² Is the value of the potential losses minus the cost of weed control (45\$US/ha for a herbicide application and 63\$US/ha for removing weeds by hand, and a price of 0.21\$US per kg of rice).

CONCLUSIONS

Weed management in Latin American rice is strongly influenced by the agroecosystem in which it is grown. Factors affecting weed infestations are sowing method used and the availability and control of water.

Irrigated rice (60% of LAC production) tends to be monocropped on the basis of favourable prices and the difficulty to turn waterlogged fields into dryland production for other crops. Two consequences of this practice have been the widespread infestation of red rice throughout the continent and the appearance of resistance to propanil in *E. colona* populations.

Weeds are one of the main constraints for rice production as a result of either upland conditions (40% of LAC production), or direct seeding of irrigated rice with suboptimal water control and land levelling. The lack of puddling and/or a permanent flood results in much heavier weed infestations when irrigated rice is direct seeded, rather than grown under transplant. Almost all irrigated rice is direct-seeded in LAC; this is one of the main differences with rice in Asia, where it is still mostly grown under transplant. Therefore, herbicide use in LAC is very intense and rice sowing rates are high to reduce weed competition. Weed control relies heavily on herbicides and represents one of the costliest inputs for rice production. Clearly, an integrated approach to weed management is needed to reduce weed control costs, rationalise herbicide use and provide effective and environmentally compatible weed control.

Efforts need to be strengthened in making available weed-free rice seed to farmers, with economic incentives to use it. In the case of noxious weeds such as red rice, certified seed should be 100% free.

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CHAPTER 12

WEED MANAGEMENT IN RICE IN AFRICA

WEED MANAGEMENT IN RICE IN AFRICA

Kwesi Ampong-Nyarko

INTRODUCTION

Rice is a strategic component of food security and a crucial element in the staple food economies of several African countries (Kaung Zan *et al.* 1985). To the observer familiar with Asian rice culture, the most notable characteristics of rice growing in Africa are its apparent newness and its primitive state. But in the time since chemical fertilisers and irrigation systems were first introduced, intensive rice growing has gained a foothold in Africa (Moormann and Juo 1986). The use of improved methods of land preparation that include levelling, bunding and irrigation has proved profitable and will expand. The main biological constraints limiting rice production in Africa include lack of high yielding improved varieties, diseases, insects pests and weeds. The important rice ecologies in Africa are upland, lowland rain-fed, deep water and irrigated ecologies. Major rice producers of rice in Africa are Madagascar, Nigeria, Guinea, Egypt, Ivory Coast, Sierra Leone, Zaire, Tanzania and Liberia.

UPLAND RICE

There are about 2.2 million ha of upland rice in Africa (IRRI 1988) which constitutes 49.8% of the total rice land. Upland rice is generally grown in the humid forest zone, where it is intercropped with other food crops (IITA 1984).

Weed problems

Weeds rank second to drought stress in reducing upland rice grain yields and quality. Yield losses caused by uncontrolled weeds in upland rice could lead to total crop loss (Akobundu and Fagade 1978; Ampong-Nyarko and De Datta 1991). Weed infestation of newly cleared forest land is known to be low compared to that of land that has been under cultivation for several years (Merlier 1973; Moody 1973). But savanna regions and short-term fallows in forest zones are characterised by heavy weed infestations that increase risk and labour requirements to uneconomic levels (Akobundu and Fagade 1978; Cates 1969). In Madagascar weeds are ranked as one of the main causes of low and declining yields in upland rice (Fujisaka *et al.* 1990).

Weed competition is more intense in upland rice than in irrigated rice because upland fields do not have standing water to suppress weed growth. Poor rice germination due to drought results in excessive weed growth, especially if semi dwarf varieties are used (Ampong-Nyarko and De Datta 1991). Common upland rice weeds in Africa include *Rotthoellia cochinchinensis* (Lour.) W.D. Clayton, *Cynodon dactylon* (L.) Pers., *Imperata cylindrica* (L.) Raeuschel, *Eleusine indica* (L.) Gaertn., *Digitaria sanguinalis* (L.) Scop., *Amaranthus spinosus* L., *Trianthema portulacastrum* L., and *Ageratum conyzoides* L. *Striga* spp. are obligate hemi-root parasites of upland rice and other cereals in the sahelian and savanna zones of Africa and this is a major constraint to the production of rice and other cereals.

Control Methods

Land preparation. Land preparation for upland rice varies greatly among regions. In west Africa, where shifting cultivation is common, slash and burn is practised with hand tools. Deep ploughing moist soil at the end of the rainy season is recommended for upland rice grown in the West African savannas (FAO 1976). Deep ploughing will bury weed seeds deep enough to prevent them from emerging. The stale seed bed technique can be used to reduce weed problems in upland rice. This technique involves the removal of successive weed flushes before planting,

by chemical mechanical or manual methods (Moody 1994). Zero tillage can be used to establish an upland rice crop where no difficult-to-control perennial weeds are found in the fallow vegetation or when appropriate herbicides such as glyphosate are available.

Planting methods. Broadcasting, dibbling or hilling are the common seeding practices for upland rice in Africa. Row drilling or dibbling in rows makes weeding and other management practices easier than in broadcast systems (Ampong-Nyarko and De Datta 1991).

Plant population. A high plant density is important for upland rice to quickly develop a canopy that will suppress weed growth. Poor stand establishment is a major concern in upland rice in Africa. In the Ivory Coast closer spacing produced rapid growth (Chabalier and Posner 1978). However under poor moisture supply, a lower seed rate is desirable.

Hand-weeding. Hand-weeding is common in Africa and although effective, it is tedious and best adapted to small holdings (Aryeetey 1970). The weed-free period required by upland rice is from 10 to 60 days after seeding (Ampong-Nyarko and De Datta 1991). Two or three well-timed weedings are enough to meet the weed-free requirement. The use of the hoe is faster but requires line sowing. Improved mechanical methods such as push-type and motorised weeders though not a common feature of upland rice in Africa, can be as effective as hand weeding in row-seeded crops.

Herbicides. Herbicide use in upland rice is feasible and effective under certain conditions such as large farms and where rice is broadcast seeded in Africa. The persistence of many pre-emergence herbicides is so short that they cannot control successive flushes of weed seedlings in upland rice (Ampong-Nyarko and De Datta 1991). This makes follow-up hand-weeding or application of post-emergence herbicides necessary. Common herbicides such as butachlor, oxadiazon, dinitramine, pendimethalin, flourodifen, propanil and MCPA have widely been tested for weed control in upland rice.

Striga in upland rice. Rice has high yield potential in the savanna zones of Africa when grown either as an upland crop or in valleys where its cultivation is expanding rapidly. The obligate hemi-root parasite *Striga* sp. is one of the main constraints limiting cereal production in this zone. Rice plants infested with *Striga hermonthica* displayed the classical symptoms of stunting and failure of panicle formation. Methods of controlling *Striga* in rice include the use of resistant varieties and cultural practices such as crop rotation, fertilisation and hand weeding.

The use of resistant varieties is the primary control measure for small farmers but it must be supported by good cultural practices (Dogget 1984). Tolerant rice genotypes to *Striga* have been identified at the ICIPE (Harahap *et al.* 1993). Genotypes confirmed resistant to *Striga* include IR 49255-B-B-5-2, IR 38547-B-B-B-7-2-2, IR 47255-B-B-5-4 and Ble Chai.

Nitrogen fertiliser tends to reduce *Striga* infestation by reducing stimulant exudation of the crop as well as slowing *Striga* development and increasing tolerance (Parker 1984). Combating *Striga* with farmyard manure is valuable, but some added nitrogenous fertiliser will prove worthwhile (Dogget 1984). Weeding out *Striga* plants is beneficial as it will help prevent about 20% yield loss that occurs after *Striga* emergence above ground and also prevents flowering of *Striga* plants. Hand pulling and hoe-weeding are the most common practices used by the small-scale farmers (Ampong-Nyarko 1994). Using trap crops that induce the germination of *Striga* seeds in rotation or as an intercrop with a susceptible crop has been reported to reduce *Striga*

infestation (Parkinson *et al.* 1986). Such trap crops include cotton, bambara, groundnut, cowpea and soybean.

RAIN-FED LOWLAND RICE

Rain-fed low-land rice also called wetland rice or hydromorphic rice, accounts for about 30% of the rice land in Africa (IRRI 1981). In West Africa rain-fed lowland rice is commonly grown in inland valleys throughout the region, particularly in Sierra Leone, Liberia, Guinea, Ivory Coast, Ghana, and the central part of Nigeria (WARDA 1980). Rain-fed lowland rice is generally grown in valleys in which some of the land is unflooded, some is occasionally flooded, and some is flooded during the major part of the cropping season (Moormann and Juo 1986)

Weed problems

Due to the lack of water control, water management is not a tool in weed management in rice fields in Africa. Aerobic conditions and high soil moisture occurring over an extended period are favourable for weed germination and growth. Once weeds become established, deeper flooding is needed to reduce weed growth. Warm, moist conditions of hydromorphic soils also favour rapid breakdown of soil applied herbicides, reducing their efficacy (Akobundu and Fagade 1978). Weed species of importance in this culture include *Cyperus* spp., *Echinochloa* spp., *Ischaemum rugosum* Salisb., *Cynodon dactylon*, *Sphenoclea zeylanica* Gaertn. and *Ipomoea* spp. In the savanna, tall grasses such as *Hyparrhenia* spp. and *Panicum* spp. are important (Akobundu and Poku 1986). Yield loss caused by uncontrolled weeds in lowland rain-fed rice in West Africa is about 40% (Akobundu and Fagade 1978).

Control Methods

Land preparation. Most rice cultivation on wetlands is for subsistence. The use of improved methods of land preparation that include levelling and bunding is not yet common but has proved profitable and will expand (Moormann and Juo 1986). Shifting cultivation is the common practice. The land is prepared manually into ridges or small heaps before flooding occurs and rice is direct seeded or transplanted (Moormann and Juo 1986). Unevenness in the field results in areas of inadequate flooding. Tillage operations are mainly done in the dry season or before flooding when the ground is hard. On large scale parastatals farms, land preparation is only done by medium or large tractors (Wanders 1986).

Varieties. Short, lodging-resistant varieties with good tillering ability are considered ideal for irrigated rice and will also perform well in hydromorphic soils not subjected to moisture stress (Masajo *et al.* 1986). However, in less favourable hydromorphic soils and shallow swamps, slightly tall plants with good tillering ability, strong culms and erect to droopy leaves are more suited to the fluctuating moistures and heavy competition from weeds. In one study in Nigeria (Akobundu and Ahiissou 1984), yield of the tall OS6 rice cultivar, which was weeded once in hydromorphic soil, was reduced by 39%, while a semi-dwarf cultivar ANDNY 11, suffered a yield reduction of 63%.

Planting. Dry seeding of rice is the common practice. Weed problems of direct seeded rice and more intense and wider in range in dry seeding (Ampong-Nyarko and De Datta 1991).

Plant population. Close spacing, between 10 and 25 cm in rows or hills, increases the ability of rice plants to compete with weeds (Ampong-Nyarko and De Datta 1991). In many areas of Africa plant density is not optimal. Tall varieties performed best when transplanted at 25 x 25

cm whereas the non-lodging varieties produced highest grain yields when transplanted 10 x 10 cm apart in Nigeria (Fagade and Ojo 1977).

Water management. At present because fields are not level and the water level is not controlled in rain-fed lowland rice in many African countries, the beneficial effect of weed suppression by flood is not realised. In most rice fields continuous flooding to a depth of 5 cm depth is required for flooding to be used as a weed control method.

Hand-weeding. Weed control in farmers' fields is often inadequate because of costs and timing of weeding. Hand-weeding is common in Africa. Weeds are allowed to grow until they are tall enough to be pulled out easily (Akobundu and Fagade 1978). The energy requirement for pulling weeds by hand and burying them with feet is about 350-400 hours per hectare (Navasero *et al.* 1986). The use of the hoe is a faster and more efficient but line sowing is a prerequisite (Curfs 1974). Two to three well-timed hand weedings should provide adequate weed control in rain-fed lowland rice (Ampong-Nyarko and De Datta 1991). Early season hand weeding especially where there is no standing water, reduces the competition of weeds for nutrients and moisture. Mechanical weeders can be used if seed is drilled or dibbled in straight rows.

Herbicides. Smallholders usually grow rice using human power. The introduction of labour-saving technology such as herbicides to supplement the hand-weeding where seasonal labour shortages occur is appropriate. The persistence of residual pre-emergence herbicides under warm moist or flooded conditions may be too low to provide a weed-free rice crop. Follow-up hand weeding or post-emergence herbicide application may be necessary. Herbicides suitable for use in rain-fed lowland rice include, bentazon, butachlor, butralin, oxadiazon, oxyfluorfen, pendimethalin, propanil, quinclorac, thiobencarb, propanil, 2,4-D or MCPA (Ampong-Nyarko and De Datta 1991).

DEEPWATER RICE

Most of 0.47 million ha of deep water rice in Africa is planted in the flood plains and inland delta of the River Niger in Guinea, Mali and Nigeria. Owing to erratic rainfall and irregular flooding, average yields usually vary between 1 to 1.5 t/ha, cultivars are often mixed, none or little fertiliser is applied and manual labour employing hoes and machetes is common (Catling 1992).

Weed Problems

Weeds are regarded as one of the more serious constraints to deepwater rice production and may result in crop failure or cause farmers to abandon their fields (Vallee and Vuong 1978; Nyoka 1983). The most troublesome weeds include *Oryza longistaminata*, *O. barthii*, *Echinochloa stagnina* and *E. pyramidalis*. Deep water rice may suffer severe weed infestation during the pre-flood period. Weed problems are often aggravated by poor stand establishment due to drought.

Control Methods

Land preparation. Before the onset of rains stubble from previous crops is burnt. Land preparation consists of one or more ploughings starting from first rains (Bidaux 1971). Deep ploughing and harrowing are recommended in the dry season if rhizomatous perennials are a problem (Ampong-Nyarko and De Datta 1991). Farmers having no serious weed problems may not plough every year (Nyoka 1983); instead they may encourage a volunteer stand of glaberrima, thus avoiding the need for ploughing, sowing and weeding.

Planting. Broadcasting rice into dry soil is common practice in deepwater rice. Seeds may be covered by hoe or left on the surface. Critical spells of drought are common which can lead to poor stand establishment and increase weed problems.

Cultivar. Rice cultivars with elongation ability, photoperiod sensitivity and tolerance to stagnant water conditions have been introduced into Africa. Farmers carefully select a cultivar with suitable duration and growth ability for the expected flooding conditions (Carpenter 1978).

Fertiliser. Small amounts of farmyard manure are used, but virtually no chemical fertiliser is used (Catling 1992). Deposits of the silt carried by rivers during annual floods provide high fertility for most deepwater rice soils. High soil fertility improves stand establishment and elongation ability of rice but weeds also grow quickly and are very competitive (Ampong-Nyarko and De Datta 1991).

Hand-weeding. Hand-weeding is the most effective weed control method in deep water and floating rice. It is particularly effective against the annual *O. barthii*; a single weeding may be used before flooding (Catling 1992). Sometimes pre-flood weeding is followed by the removal of any large weeds after the floods have arrived. In severe infestations of *O. longistaminata*, *O. barthii* and other grasses such as *Echinochloa*, *Brachiara* sp. and *Acroceras amplexans*, water mowing, a drastic form of weeding, where the farmer decides to forfeit the crop for that year and cut off the whole field during the early flooding period is carried out (Martin and Guegan 1973; Nyoka 1983; Catling 1992).

Herbicides. Virtually no herbicides are used in deepwater rice in Africa. However, most common weeds present before flooding can be controlled by herbicides. Butachlor, oxadiazon, pendimethalin, thiobencarb, piperophos-dimethametryn and oxyflorfen are effective when applied pre-emergence (Ampong-Nyarko and De Datta 1991). Residual herbicides give variable results when applied to dry soils or when flash floods occur soon after application.

Other control methods. Weeds are cut for cattle feed, and sheep and goats are put to graze the fields (Catling 1992). Panicles and shattered seeds of wild rice and weeds such as *Echinochloa stagnina*, *E. colona*, *Brachiara deflexa* are also gathered for human consumption, especially during the drought years (Catling 1992).

IRRIGATED RICE

In sub-Saharan Africa irrigated rice comprises 11.3% of total rice growing area (Kaung Zan *et al.* 1985). In Egypt, ricelands are entirely irrigated.

Weed Problems

The major weeds in irrigated rice are *Cyperus* spp., *Paspalum* spp., *C. datycton*, *I. rugosum*, *Echinochloa* spp., *Sacciolepis* spp., *Spheonoclea zeylanica*, *Ipomoea* spp.. Both large-scale and small-scale rice growing areas in tropical Africa have little water control. As optimal water depth is not maintained, weeds grow and infest irrigated fields. In poorly flooded rice fields most semi-aquatic lowland rice weeds can germinate and survive (Ampong-Nyarko and De Datta 1991). When improved weed control practices are compared with farmers practices, the increase in rice yield is often about 10% (Kaung Zan *et al.* 1985).

Control Methods

Land preparation. Proper land preparation is essential for good stands and crop growth. In Africa land is mainly prepared by manual labour using a short-handled hoe. In tsetse-free areas, draught animals are being introduced and their use is slowly increasing (Kaung Zan *et al.* 1985). In large rice production parastatals, such as those in Nigeria, Cameroon, Kenya, Madagascar, Ivory Coast, Senegal and Tanzania, land preparation is mechanised and may consist of wet rotovation. Small power tillers have also been introduced in countries such as Sierra Leone.

Stand establishment method. Transplanting and direct seeding are practised. For transplanting, rice seedlings are raised in a wetbed nursery and then transplanted manually by farmers. Transplanting healthy 20- to 30-day old rice in rows in well-prepared weed-free fields gives the rice a head start over weeds.

Plant population. Closer spacing increases a rice crop's competitive ability against weeds. In many parts of Africa farmers still use traditional cultivation practices; in particular random planting. A big variation in plant density occurs from farm to farm; recommended optimum densities are difficult to achieve because of the practical problems of transplanting in rows (Njokah and Okhoba 1985).

Water management. Water management will eliminate the usual upland weeds in transplanted irrigated rice; anaerobic conditions in soil under 5 cm of water inhibits most weed growth (Ampong-Nyarko and De Datta 1991). In both large-scale and small-scale rice growing areas in tropical Africa optimum water depth is not maintained, and as a result, weeds grow and infest irrigated fields.

Fertiliser. The response of rice to fertiliser is markedly increased by effective weed control. Fertiliser use in African rice culture is still very low because under the traditional cultivation of rice, fertility is restored through the bush fallow system (Kuang Zan *et al.* 1985).

Hand-weeding. In several African countries hand-weeding is the most common practice among small farmers. Hand weeding in many rice areas of West Africa can require 250-780 hours/ha, depending on the ecosystem, frequency of weeding and environmental conditions. The first six weeks after transplanting is the critical period of weed competition. Two or three timely weedings will provide adequate weed control. Rising labour costs and scarcity of labour at the time of weeding has enkindled interest in mechanical weeders.

Herbicides. Herbicide use in Africa is still limited. The persistence of residual pre-emergence herbicides under warm moist or flooded conditions may be too low to provide a weed-free rice crop. Follow-up hand weeding or post-emergence herbicide application may be necessary. Rice herbicides show maximum selectivity in transplanted rice because of differences in growth between rice seedlings and the germinating weed seedlings. Applying a pre-emergence herbicide together with effective water management will provide season-long weed control. In direct seeded irrigated rice the number of herbicides that can be used safely may be limited. Herbicides suitable for use in irrigated transplanted rice include bensulfuron, bentazon, butachlor, 2,4-D, oxadiazon, pendimethalin, propanil, quinclorac and thiobencarb (Ampong-Nyarko and De Datta 1991). In direct seeded rice, butachlor, thiobencarb, butachlor, and propanil are effective and have been well tested.

ENVIRONMENTALLY SUSTAINABLE WEED MANAGEMENT

Environmentally sustainable weed management is the rational use of environmentally safe and integrated weed management tactics to provide sustainable protection of crops from the ravages of weeds. Indirect tactics for weed control in rice include land preparation, water management, plant spacing, seed rate, cultivar and fertiliser application. The essential factor in any environmentally sustainable weed management is the number of indirect and direct tactics that can be combined economically in a given situation. Farmers are interested in net benefits and in minimising risks. Agronomic practices such as water management, which indirectly suppresses weeds and fertiliser application which increases the competitive ability of rice, are highly economical. Combined with any of the direct weed control methods such as hand-weeding, these practices can constitute an economically viable production system (Ampong-Nyarko and De Datta 1991).

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CHAPTER 13

HERBICIDE RESISTANCE IN RICE: STATUS, CAUSES AND PREVENTION

HERBICIDE RESISTANCE IN RICE: STATUS, CAUSES AND PREVENTION.

Jonathan Gressel and Aurora M. Baltazar

INTRODUCTION

Herbicides have allowed plant breeders to produce cultivars that do not need to compete with weeds for space, light, water and minerals; concentrating mainly on yield; allowing the feeding of an over-expanding human population. This is especially evident with rice, where the lowering of the stature reduced partitioning of photosynthate into straw, greatly increasing the yield index. The green revolution rice, grown in large areas, has magically turned hunger into self sufficiency.

There is a dark side to this success story; monoculture of green revolution crops was encouraged, and the lack of height renders the crops far less competitive with weeds, and herbicide use became obligatory. Resistance is an inevitable outcome of relying on single methods. For the first 35 years of heavy herbicide use beginning after World War II, there were only sporadic cases of resistance, but lately there has been an evolutionary vengeance that has stimulated worry, and the first thoughts on mandated management strategies. The reasons for the initial slow and now rapid evolution will be examined so that we may more wisely advise strategies to retain safe herbicides in our never ending war with weeds. Some cases, like the broad spectrum cross-resistances and multiple resistances to wheat-selective herbicides that have evolved in Australia, will require deep thought and novel strategies to find solutions.

This chapter will attempt to summarize what has been happening, why, and how resistance can be prevented, delayed, contained or ameliorated. A special emphasis will be placed on the problems facing rice, and how they can be addressed. Rice should, at first glance be a crop redolent with cases of herbicide resistance based on analogies with other cases of resistance. Herbicide-resistant weed populations evolved in other monocultures; maize, wheat, tree crops and roadsides, yet until recently the cases in rice were minimal. Thus, we will have to explore the reasons and analyze whether they are due to the nature of the cropping system, the weeds of rice, and/or the nature of the herbicides and herbicide mixtures used. This is done while analyzing the causes that facilitated resistance to evolve in rice and compare them with the cases in other crops, to learn how to prevent or delay their further occurrence in rice. When a farmer has a good herbicide system for weed control, measures should be taken to prevent the loss of such tools.

Changes in Weed Spectrum vs. Resistance

Changes in weed spectrum due to changing technologies are not new. Many previously pernicious weeds have been virtually eliminated. Seed cleaning equipment eliminated some weeds, deep cultivation eliminated many perennials, draining eliminated wetland weeds, fertilizers selected against those that did not respond well and they disappeared as weeds, as will remain rare innocuous wild plants (Haas and Streibig 1982; Gressel and Kleifeld 1994). Rotations kept many weeds at bay. Wheat in winter, rice in monsoon season as a rotation, eliminated most weeds of wheat, but left *Phalaris minor* Retz., unaffected by paddyng, as a major weed in Indian wheat.

Weeds often mimic crops in morphology and phenology (Barrett 1983). The rotation of crops having different phenologies and morphologies prevents any species from building up to the

explosive levels that are possible in monoculture. Herbicide rotations had the same effect, as different herbicides left behind different weeds, and herbicide rotations controlled most weeds at some time during the rotational cycle. Rice fields were transformed from colourful to drab green with the advent of 2,4-D and the control of broad leaf weeds in the mid 1940's. As ecology abhors a vacuum, all empty niches are rapidly filled in monoherbicide monoculture by weeds that were always resistant (e.g. grasses that were naturally resistant to 2,4-D in rice). Later, resistances evolved in species previously controlled. The message herein is that the farmers and their advisors can no longer rely on indiscriminate spray, spray, spray. They must understand the crop, its weeds, the physiological and biochemical modes of action of herbicides, as well as crop resistance to the available herbicides, and the full implications of each herbicide-use. Only then should farmers decide when to treat and when not, and with what to treat and what not, and how to set up wise rotations. Alternatives to herbicides must be sought, so that we will still have the herbicides available when needed.

Many times a lack of control, due to a variety of reasons, is misconstrued as resistance. If a number of weed species remain after treatment that should have controlled them, this is a lack of control. If one species remains that should have been easily controlled, but harder to control weeds were killed; there is a good chance that resistance has evolved.

There are enormous pressures being imposed to lower pesticide use based on some real and some perceived dangers to humanity and the environment. Agricultural economists have been teaming up with weed scientists to provide computer programs for delineating the thresholds showing when herbicides provide cost-effective weed control, cutting out unneeded treatments. The economists' "less is better" can fit well with the ecologists' "use less", resulting in less expensive weed control, less environmental impact and often less, or delayed resistance. Unwisely using less can also enhance the rate of evolution of resistance (see below). Thus, we must learn how to use less, but to do so intelligently.

Definitions. *Herbicide resistance* is "the inherited ability not to be controlled by a herbicide". The term *resistance* should always be followed and/or preceded by modifiers. An important modifier is the rate applied. Resistance to agricultural rates is assumed here, but rates should be stated. Thus, with a selective herbicide, rice is *naturally resistant*. Evolution of resistance is then the process whereby the rare resistant individual becomes the majority - i.e., a *resistant population*. The *resistance factor* is usually described as the I_{50} of the resistant individual divided by the I_{50} for the susceptible. The resistance factor for the I_{50} to I_{50} is harder to measure but is more significant for field situations, and need not be the same as for I_{50} s. There may be *full resistance* at an agricultural use-rate, or *partial resistance*. The latter occurs when the plant is severely inhibited but still produces some seed. Tolerance was previously used for partial resistance (LeBaron and Gressel 1982), but this meant different things to different researchers, and has been dropped (Gressel *et al.* 1995).

Some species have evolved resistance to more than one herbicide. If this is due to sequential selection (one herbicide was used until resistant populations evolved, then another was used and resistance evolved to it), this is *multiple resistance*. These are separate evolutionary events due to mutations in different genes. If evolution of resistance to one herbicide immediately endowed resistance to other herbicides there is *cross resistance*. It is *target-site cross-resistance* if all the herbicides affect the same precise target or *metabolic cross resistance* if all the herbicides or their toxic products are degraded by the same mechanism. *Negative cross*

resistance occurs when the resistant plant is more susceptible to some other herbicide than the wild susceptible biotype.

FACTORS GOVERNING THE RATE OF EVOLUTION OF RESISTANCE

If the relative importance of each of the factors controlling the rates of evolution is understood, cultural practices can be modified to delay resistance. The relative importance of each factor can be assessed by modelling and verified by epidemiology (hindsight elsewhere) and/or experimentation. Much of the hard biological and chemical data needed for testing the models is lacking. The first model describing different rates of evolution of herbicide resistance under different conditions was published about 17 years ago (Gressel and Segel 1978). The basic model has remained, but it has been modified through the years to consider more information that has appeared (Gressel and Segel 1982; 1990a). Other groups have rightly started designing more sophisticated models (Maxwell *et al.* 1990; Mortimer *et al.* 1992).

A major advantage of models, besides their assistance in prediction, is that they identify gaps of knowledge. This in turn can suggest priorities for research. Surprisingly, there are no major differences in the predictions about rates of evolution among the models, although there are differences in modelled effects of ameliorative treatments once resistant populations have appeared. Models must explain why the vast majority of cases of resistance have appeared in monoculture, monoherbicide situations. Monoherbicide is defined as consecutively/continually using one or more herbicides with the same precise site of action, or one or more herbicides that are degraded in the same manner, or whose toxic products are degraded in the same manner for the control of a given weed. There are many cases where a large number of generations were treated with a given herbicide, but not in consecutive years, due to herbicide rotation, and resistance did not evolve. The same numbers of treatments in monoherbicide culture elicited resistance.

Factors Modulating Evolution of Resistance

The factors in the models are usually the same, although an earlier model lumped many together under the same heading (Gressel and Segel 1978). These factors include:

The initial frequency of resistant mutations in the gene pool. Mutations are always occurring, whether we use a herbicide or not. Most mutations are lethal and the mutants disappear. Virtually all of the non-lethal mutants are somewhat deleterious in the "pristine" herbicide free environment. Thus, most mutants are found in a population at a frequency lower than the natural mutation frequency because of these inadequacies, when the mutants are in competition with more fit genotypes.

Genes conferring resistances to the various herbicides are in populations at different natural frequencies. A few experiments with acetolactate synthase inhibiting herbicides (sulfonylureas, imidazolinones, etc.) have shown that about one in a million plants bears a semi-dominant nuclear mutation in the target site conferring resistance. In contrast, target-site photosystem II resistance is recessively inherited on the *psbA* gene of the chloroplast (LeBaron and Gressel 1982). Chloroplast mutations appear phenotypically at far lower frequencies than nuclear mutations, frequencies that can only be guessed to be near 10^{-20} . Thus resistance to photosystem II inhibiting herbicides such as the triazines, phenylureas and propanil can be expected to evolve resistant populations much more slowly than sulfonylurea resistance, based on the time it would take for a resistant individual to predominate in a population. Indeed, sulfonylurea resistance

appeared within 3 years of use in rice whereas populations resistant to PSII herbicides were only evident after >15 years of continual use on a much larger scale in rice, and the resistance to propanil is not in the target site.

The frequency of resistance to some herbicides, such as the auxin types, the thiocarbamates, the chloroacetamides is unknown. They are thought to be multi-site inhibitors (mainly because no specific sites have been found). Thus, to have target site resistance, you would have to *compound* the frequencies of resistance to each target to get a resistant individual. For instance, if a thiocarbamate affects 7 targets in a weed and each target is mutated to resistance in one plant in a million, then there would be one plant resistant to the herbicide in $10^{7 \times 7} = 10^{49}$. There are probably not 10^{42} seeds of any given weed to choose from in the world, so evolution of multi target-site resistance would be unlikely or take very long to evolve. A weed would have to "learn" to degrade a thiocarbamate, i.e. to evolve levels of a metabolic pathway to detoxify the herbicide before it kills the weed. We do not know the frequencies of detoxification mutants, but from history, it is clear that they must be rarer than single target site mutations at normally used use rates. Detoxifying mutants can be found more frequently when lower rates are used and single gene target-site mutants are more frequent at high use rates (Gressel 1995).

Selection pressure - the greatest influence. Selection pressure is the relative ability exerted by a herbicide to decimate the wild type and leave resistant individuals. Some herbicides exert greater selection pressure than others, i.e. remove more susceptibles over the season than others.

The selection pressure of the same herbicide can be different on different weed species. The totality of factors included in selection pressure is measured as the ratio of survival of resistant to susceptible propagules over a growing season. Selection pressure is heavily affected by herbicide persistence. The longer a herbicide remains active, the greater its selection pressure, when weeds germinate throughout the season. Any given flush germinating after a low residual herbicide has sufficiently dissipated will leave susceptible plants, which produce susceptible seeds. This gives a low selection pressure. This is probably the major reason why widespread resistance has not evolved to 2,4-D even though there have been more "hectare-years" of this herbicide used than any other. Many weed species can produce a complete life cycle of miniature plants with susceptible seeds as an innocuous understory in the crop, after 2,4-D has dissipated, leaving susceptible seed, which will depress the rate of evolution of 2,4-D resistance by diluting out any resistant individuals that appear.

Post-emergence herbicide use exerts lower selection pressure in many crops because some weed plants are missed due to shading, resulting in unequal distribution. This is less likely in paddy rice when the herbicide can diffuse in the water, and all weed plants are affected.

Some rice herbicides exert exceedingly strong selection pressures because of their persistence. Bensulfuron-methyl, dimethametryn, pendimethalin are often residual in soil at levels that still control many weed species (and often susceptible crops) a year or more after application. It is not surprising that incidences of resistance to persistent herbicides are widespread. Resistance to triazines (mainly atrazine, an analog of dimethametryn) on a worldwide scale appeared first in broad leaf weeds having an L_{50} ten fold or less than the rates used. Resistance evolved later in the harder to control grass weeds requiring more herbicides, often where triazines were used as 'sterilants' along roadsides.

Resistance has also evolved to herbicides having no biological persistence. Paraquat is biologically ephemeral within hours. In many cases farmer persistence replaced chemical persistence. When farmers spray paraquat monthly for five years, this is like bensulfuron-methyl persistence. Persistence is also related to weed biology. If a weed germinates in a single flush in an agronomic situation, a herbicide with a short persistence at the time of that flush will exert high selection pressure. This may well be an important factor in difenzoquat/triallate resistance in *Avena fatua* L. in Canada, U.S.A. and Israeli grain fields, and *Lolium* resistances to diclofop-methyl. These herbicides do not have the persistence of bensulfuron-methyl or dimethametryn.

Relationship between mutation frequency, selection pressure and herbicide rate. Target site mutations usually confer such a high level of resistance that they are selected for at all agricultural rates. If the farmer lowers the rate of application of a herbicide, the selection pressure for the target site mutant is lowered because more susceptibles will survive. This is not the case for polygenically inherited resistances, where each of the polygenes usually gives only a small increment of resistance, often due to metabolism. If the herbicide is applied at a high rate, and for example four increments of resistance are needed, four mutations would have to be found in the same individual. If each mutant is found at a frequency of 10^{-6} , then the likelihood of a resistant individual being found is 10^{-24} . If the four genes are to be chosen from a large family of polygenes (e.g. 100) then the likelihood of four mutations in one individual are $10^{-24} \times 10^2 = 10^{-22}$, still a very low frequency. Conversely, if the farmer uses a low rate, and only one increment is required, and there are a hundred polygenes to choose from, each at a frequency of 10^{-6} , then there will be a resistant individual in $10^6 \times 10 = 10^7$ of the plants. Thus, high rates exert a selection pressure for monogenic, target site resistances and low rates for polygenically inherited resistance. There is evidence that this has happened with the same herbicide in the same weed genus in the same crop in different places in the world (Gressel 1993) and models have been proposed rotating low with medium doses to delay such evolution (Gressel 1995).

Fitness - a major modulator. Most mutants are less fit than the wild type when the selector is not present, otherwise the mutant would be the wild type. This should be measured as competition between the resistant mutant and the susceptible wild type. Under such competitive situations, triazine-resistant mutants have 10-50% the seed yield of the susceptible wild type (Gressel and Segel 1978, 1990a; LeBaron and Gressel 1982). Triazine and other resistant biotypes are often even less productive when grown alone (Gressel and Segel 1990a). There is a possibility that where the modifications conferring resistance in a target enzyme are far from the active site of the enzyme, as occurred with sulfonylurea resistance (Schloss *et al.* 1988) that the fitness differential could be minimal.

Fitness should be measured as competition with wild type over a complete life cycle, preferably in an agroecosystem. Unfortunately this stricture is too often ignored and there are many studies purporting not to find fitness differentials, where true fitness loss was actually not measured. With low persistence herbicides, susceptible weeds can compete with the less fit, resistant weeds after the herbicide has dissipated, suppressing the relative yield of resistant seed where the weed has multiple flushes of germination. Differential fitness will not assist in delaying the rate of evolution of resistance to high persistence herbicides used in monoherbicide culture; there is no occasion for the fitness difference to be expressed. Herbicide rotation can allow for fitness to depress the rate of enrichment of resistant individuals in a population, but only in the "off" years when the particular herbicide is not used. The models of resistance-suppressing rotational strategies suggest that if there is adequate weed control in the years when a different herbicide

is used, one can keep even a herbicide with a high initial frequency of resistance in use for many years (Gressel and Segel 1990a). There are even some strategies where there is negative enrichment for resistance or just a negligible enrichment of resistance. These strategies do not preclude the use of herbicides in the off years; they require that the "off" year herbicides do not select for the same resistance genes as the "on" year herbicides (Gressel and Segel 1990b). This requires understanding the weeds and the herbicides.

The soil seed bank. Much weed seed is incorporated into the soil seed bank by cultivation, and proportions are released each year when they reach the surface and/or dormancy is overcome. After starting to treat with herbicide, the few resistant seeds entering the soil are diluted by the susceptible seed from previous years. The longer the life in the seedbank, the greater the buffering effect of susceptible seed from previous years, decreasing the rate of evolution of resistance. There are field data to support this: *Senecio vulgaris* L. has evolved triazine resistance in orchards, nurseries and roadsides where there was no mechanical cultivation, but not in cultivated maize fields. *Senecio* seed is incorporated into the soil seed bank in cultivated fields, where it is viable for many years (Watson *et al.* 1987). All *Senecio* seed falling on undisturbed soil on roadsides or orchards either germinates, or dies during the following season (Putwain *et al.* 1982). Thus, the epidemiological evidence corroborates the prediction that resistance evolved where there was the shortest average seed bank life time. Such information must be considered in formulating strategies for resistance management. Many other species such as *Lolium* do not enter the seed-bank under specific agronomic situations, i.e. in minimum-tillage agriculture, partly explaining the propensity for rapid *Lolium* evolution in Australia. In cases of limited seed bank it is clear why rotational strategies can be so effective; crops can be used that confuse weed phenology, and alternate herbicides can be used to control the weed if rotations are well designed.

Integrating the Factors into Models

A populations dynamics model was elaborated, based on a series of complicated equations and then many simplifications. The summary equation is:

$$N_n = N_0 (1 + f a \bar{N})^n$$

where n is the number of years of treatment; N_n is the proportion of resistant of a given species in the n^{th} year of continued treatment of a given herbicide. N_0 is the initial frequency in the field prior to herbicide treatment, which is controlled by the frequency of natural mutations to the resistant biotype, and the fitness of such a biotype. The factor in parentheses governs the rate of increase of resistance. It contains the overall fitness (f) of the resistant compared to the susceptible biotype, which in the many cases of triazine resistance is between 0.3 and 0.5. The selection pressure (a) is defined as the proportion of the remaining resistant divided by the proportion of remaining susceptibles at the end of a growing season. For example, if no resistant are killed and 90% of the susceptibles are killed, $a = 1/0.01 = 10$. Selection pressure and fitness are divided by $\bar{N}$, the average life-span of the species in the soil seed-bank. In weeds that germinate immediately, such as *Senecio* on roadsides (but not in ploughed fields) $\bar{N}$ equals one year. With most weed species in cultivation, $\bar{N}$ is between two and five years. An increase in $\bar{N}$ depresses the rate at which resistance will increase. More elaborate models have been subsequently constructed (Maxwell *et al.* 1990; Mortimer *et al.* 1992).

The interrelations are clearer when we use the equation to generate hypothetical slopes from different selection pressures and from an average seed-bank life-span, with different fitnesses

(Fig. 1). We have started in year zero with a frequency of 10^{-10} as might occur if resistance was inherited by a single recessive gene in a diploid weed.

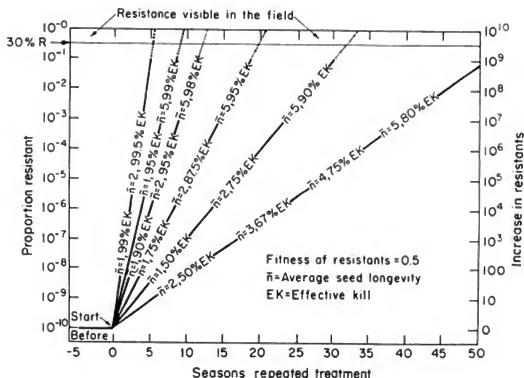


Figure 1. Effects of various combinations of selection pressure (a) (measured as season-long effective kill, EK) and of soil seed-bank longevity ($\bar{N}$) on the rates of enrichment of herbicide-resistant individuals over many seasons of repeated treatment. The values are plotted for fitnesses that would be allowed to develop after the herbicide becomes degraded. With the persistent triazine-type herbicides the fitness (f) would be near to unity, as the fitness differential has no time to become apparent. With the phenoxy type herbicides, fitness differentials ($f = 0.4-0.6$) will have time to be influential. Resistance (R) would become apparent in the field only when more than 30% of the plants are resistant. The scale on the right indicates the increase in resistance from any unknown initial frequency of resistance in the population; the scale on the left starts from a theoretically expected frequency of a recessive monogene. Plotted from equations in Gressel and Segel (1978).

It is possible to move the frequency scale in Figure 1 to fit any other initial field frequency. From the slopes, it is clear that the proportion of herbicide-resistant individuals would increase year by year. The slopes indicate that it will take many years to reach a frequency of resistant weeds that will be noticeable (i.e. more than the 1-10% viable weeds that usually remain after a herbicide treatment). Thus, farmers do not realise that they are enriching for herbicide resistance until it is upon them.

Such models allow one to plot scenarios as is done in Figure 1. One can easily surmise that the very abrupt slope with rapid evolution of resistance is a pretty good summary of what actually happened with persistent sulfonylureas and triazines. The reason that resistance typically appears to the former after 3-5 years of use and the latter 7-10 years. This is probably due to the

much lower initial frequency of chloroplast-inherited triazine resistance in the population and the high initial frequency of nuclearly inherited sulfonylurea resistance.

The lower more obtuse-angled slopes showing slow evolution are typical of post-emergence herbicides with imperfect cover, missing a proportion of the weeds and lowering selection pressure. Additionally, weeds completing life cycles before application, or after dissipation of the herbicide slow evolution, as with non-persistent 2,4-D and propanil. This is because these early or late weeds produce susceptible seed diluting resistance. Field epidemiology has clearly shown that these models work only in monoherbicide culture. If it takes seven years for resistant populations to appear in monoherbicide cultures, it has typically taken much more than 14 years when the herbicide is used every other year. Even the models that consider fitness differentials, seed bank etc., during rotation (Gressel and Segel 1990a) seem to underestimate the value of rotations in delaying resistance.

Negative Cross Resistance in Rotations to Delay Resistances

Some herbicides are more toxic to individuals resistant to other herbicides than to susceptible ones, i.e. there is negative cross resistance. Negative cross resistance can be elucidated and incorporated into rotational strategies for preventing resistance, both before and after populations become resistant. The delaying effect of negative cross resistance must be added or compounded to the lack of fitness of resistant weeds, when considering rotations. The instances of negative cross-resistances in atrazine-resistant weeds include herbicides that act at or near the same site in photosystem II (dinoseb and pyridate) as well as herbicides acting on other photosystems (paraquat). There is negative cross-resistance to other tubulin binding herbicides in dinitroaniline resistant *Eleusine*, but not to six commercial herbicides on this weed (Vaughn *et al.* 1987). Much of the data on negative cross resistance is from *in vitro* studies, the rest from small scale pot studies, often without full dose response curves (Gressel and Segel 1990b). There is interesting recent studies with pyridate strongly inhibiting triazine-resistant weeds far more than the sensitive one (Arlt and Jüttersonke 1992; De Prado *et al.* 1992). There is a lack of field data on this potentially powerful tool to prevent resistance from evolving.

A recent model (Gressel and Segel 1990b) shows how by utilizing negative cross resistance there can even be a "negative enrichment" where the resistant individuals are depleted to a lower than natural frequency at normally used rates. This can be illustrated by plots using a modified form of Eq. 1. (Figure 2). For example, the mixtures presently used may well affect atrazine-resistant biotypes to a far greater extent than the sensitive biotypes. The selection pressure is then negative as shown in Figure 2 (dashed line). This is probably the case with pyridate, which is heavily used (in mixture with atrazine) to control atrazine-resistant weeds. One should clearly look for herbicides exerting negative cross resistance to control propanil-resistant *Echinochloa* spp..

Seemingly, farmers could use lower rates of these herbicides with negative cross resistance to achieve the identical level of weed control of the resistant biotypes where resistant populations predominate. When rates are thus balanced, there will be no selection pressure for resistance and no enrichment of resistance in the population (Figure 2, thick line). This could be used prophylactically i.e. before resistant populations predominate or just after resistance occurs. Lower rates will be much more "cost effective" than full rates, and can preclude crop

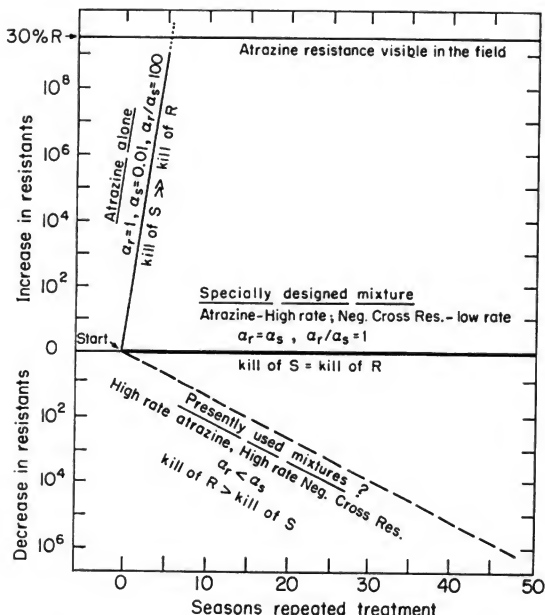


Figure 2. Modelling the effect of negative cross resistance on resistant weed evolution: atrazine as an example. Note: the frequency of resistance is shown on an exponential scale (from Gressel and Segel 1990b).

Thin line: The presumed rate of evolution of atrazine resistance when no other herbicide is used. It is assumed that the herbicide is ineffective on resistant individuals and has less than 99% effective kill (season long suppression of seed output) of susceptible individuals. **Thick line:** The effect of herbicides having strong negative cross resistance when mixed with atrazine at normal use rates. These other herbicides control resistant biotypes more effectively than atrazine affects the susceptible biotype. **Dashed line:** The effect of specially balanced mixtures with atrazine at a (normal rate) and a herbicide having negative cross resistance used at a low rate. The rates are balanced and atrazine controls the susceptible biotype to the same extent that the mixed herbicide controls the resistant biotype. It is assumed that the mixed herbicide is ineffective on the susceptible biotype at this rate.

phytotoxicity problems. Those involved with production of herbicides and those engaged in management of weeds are encouraged to try to obtain the necessary data and test the strategy in field situations. In places where resistant populations have evolved, the depletion of resistant

populations should be followed, using various rates of the herbicide exerting negative cross-resistance.

Mixtures as Tools to Delay/Prevent Resistance

Besides the mixtures having negative cross-resistance there can be simple heterologous mixtures as well as synergistic mixtures. These can be interrelated and/or overlapping with each other and with mixtures exerting negative cross-resistance. Heterologous mixtures are of more than one herbicides acting on the same weed at different sites of action. The best documented case is that of alachlor and atrazine, which both control *Amaranthus* spp. and *Chenopodium* spp., species often evolving triazine resistance.

The effect of mixtures with partially overlapping weed spectra is manifold. One effect is to lower the initial frequency by compounding the frequencies of resistance to each herbicide in those weeds controlled by both. If the frequency of resistance to one herbicide is 10^{-7} and that of the other is 10^{-5} , the compounded frequency to both is 10^{-12} . If all else is equal, it will take at least twice as long for resistance to evolve. As fitness losses are also compounded, it should take longer yet, giving a synergistic effect on resistance management. In the case of the alachlor/atrazine mixture, there is no information on the frequency of resistance to either herbicide. Resistance to alachlor (or other chloroacetamides) is exceedingly rare despite widespread use. There probably can be no target site resistant resistance to alachlor or butachlor; the target is unknown, suggesting that there are more than one target.

A synergistic mixture in the general sense is one where the herbicidal effect of the mixture is greater than the effect of the sum of the components. This allows using less of each component, often giving an economic advantage to a mixture. The atrazine-alachlor mixture has been shown to be synergistic against some weeds (cf. Gressel 1990) and smart farmers have reduced their rates. The lowering of the rates lowers the selection pressure for resistance to each herbicide, lowering the rate of evolution for each. This effect is synergistic beyond the compounded frequencies.

Another type of synergistic mixture is one containing a herbicide and an otherwise inactive adjuvant. Synergistic adjuvants are used to control insecticide-resistant insects that evolved high levels of monooxygenases. Laboratory studies indicated that the addition of monooxygenase inhibitors allows control of the *Alopecurus* and *Lolium* that evolved cross-resistance to wheat selective herbicides (Gressel 1990; Kemp and Caseley 1991; Powles and Matthews 1992). Some insecticides have been shown to have unwanted synergies with herbicides, especially propanil, severely affecting the rice crop (Matsunaka 1968).

Criteria for Using Mixtures

Mixtures did not prevent or greatly delay the evolution of resistance in many situations with insecticides and fungicides confounding original hopes. As herbicide mixtures are commonly used in rice, it is imperative to delineate criteria for use of mixtures. This has been discussed at length in Wrubel and Gressel (1994).

It has been postulated that the use of herbicide mixtures combining different modes of action will substantially delay or preclude evolution of resistance to the more vulnerable or at-risk herbicides (Anonymous 1990; Anonymous 1991a,b). This is because weeds resistant to the

vulnerable herbicide will be destroyed by the mixing partner, or at least be rendered relatively unfit compared to the wild type.

Spectra of weeds controlled. For our discussion we will assume that two herbicides are used in mixture although more are possible. We refer to "mixtures" as only those combinations of herbicides where both partners affect the same target weed (Table 1, species A). Often mixtures are used where each partner affects different weed spectra, e.g., mixtures of grass and broadleaf herbicides (species B and C in Table 1). These latter mixtures, which increase weed control benefits, have no influence in delaying evolution of resistance in weeds they do not affect. They might even exacerbate resistance by controlling competing weeds, creating a more open niche for resistant biotypes. It is hard to assess, without experimentation, what the effect on the rate of evolution will be when the mixing partner has a moderate effect on a species excellently controlled by the vulnerable herbicide (Table 1, species D).

Table 1. Possible effects of mixtures on different species.

Control by	Species			
	A	B	C	D
	(level of control)			
Vulnerable herbicide	++	++	0	++
Mixing partner	++	0	++	+

0 = no control; +=partial control; ++=control

Source: Wrubel and Gressel (1994)

The mixing partner must effectively kill or severely weaken the weeds most sensitive to the vulnerable herbicide, because these weeds are the most likely to evolve resistance (Gressel and Segel 1982; Maxwell *et al.* 1990). Both components should do so with nearly the same effectiveness; it may not be helpful if at the rate used, the mixing partner kills 75% of the weeds and the vulnerable kills 95%, unless the 20% remaining are severely inhibited such that they have a lesser reproductive capacity than the wild type. Otherwise, resistance could quickly evolve in the remaining 20% of weeds.

Persistence of components. Both components of a mixture need to have similar persistence or the mixing partner must have longer persistence than the vulnerable herbicide when weeds germinate throughout the cropping season. Otherwise, there will be a period when only the vulnerable one is present and the target weed will not be exposed to a mixture at all (Figure 3A). Unlike crops, which have been selected to germinate uniformly and shortly after planting, seeds of many weed species have many flushes of germination during a cropping season (Bewley and Black 1982). If a susceptible weed has multiple flushes during the season, and the vulnerable herbicide has a longer period of activity than the mixing partner, then the vulnerable herbicide selects for individuals resistant only to it after the mixing partner has dissipated (Figure 3A). Thus, if the vulnerable herbicide has season-long activity, it is often critical that the mixing partner have the same persistence. This problem is accentuated when there is a long growing season and there can be more flushes of weeds producing viable seed in late season. Thus, a

mixture may be more efficacious in short season growing areas than in areas with very long growing seasons. Rice herbicides vary considerably in their persistence (Table 2).

A mixture that is not well matched for persistence can still be effective if the weeds germinate in a "single flush", without further germination, and both herbicides outlast the flush with equal efficacy (Figure 3B). Most cropping systems have many different weed species, so this circumstance can hold for some species but may often be irrelevant for the agroecosystem as a whole.

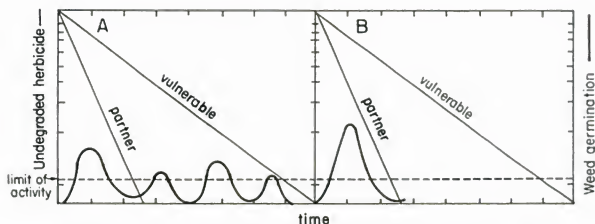


Figure 3. The persistence of herbicides in mixtures as related to germination flushes of weeds. The dissipation of herbicides is usually linear when herbicide remaining is plotted exponentially. The horizontal dashed line denotes when the herbicide is no longer biologically active. A. A situation where a weed species germinates throughout the growing season and many flushes are affected by only one component of a mixture. B. A situation where the weed species germinates in a single flush and is affected by both components of the mixtures. Source: Reprinted from Wrubel and Gressel (1994).

Target sites of action. The mixing partner should have a different target site of action from the vulnerable herbicide. Thus, use of a triazine and a uracil or phenylurea can be contraindicated as partners for propanil, as they act on the same protein in photosystem II. The situation for ALS-inhibitors is slightly more complex because of the differential pattern of cross-resistance among weed species to ALS-inhibitor herbicides (Gabard *et al.* 1989; Hattori *et al.* 1991; Saari *et al.* 1994; Saxena and King 1990). This pattern probably results in part from different or overlapping active sites for the herbicides on the ALS molecule (Schloss *et al.* 1988). All weed biotypes resistant to one ALS-inhibitor are cross-resistant to at least some other ALS-inhibitors (Saari *et al.* 1994), and it is yet impossible to predict the pattern of cross-resistance. Additionally, whereas one biotype of a species may have limited cross-resistance to other ALS-inhibitors, other biotypes of the same species may have broader overlapping spectra, i.e. the genes are present for broad spectrum ALS resistance. Thus, two ALS-inhibitors cannot be considered mixing partners for resistance management. The variety of rice herbicides that can be considered for use in mixtures is summarized in Table 2.

Modes of herbicide degradation. The mixing partner should not be degraded in the same manner as the vulnerable herbicide. For example, if propanil, a somewhat vulnerable herbicide is degraded in the crop by arylacylamidase, the mixing partner should have no chemical site that

can be attacked by that enzyme. This criterion could be a problem in wheat where all biochemically-selective herbicides seem to be degraded by monooxygenases in the crop (Gressel 1988). Herbicide mixtures for wheat would be subject to evolution of resistance in weeds capable of evolving increased levels of monooxygenase detoxification systems. This can come about by the evolution of higher levels of specific monooxygenases, by mutations coding for enhanced substrate (herbicide) specificity of one monooxygenase, or by mutations enhancing higher constitutive levels of all or many monooxygenases.

Partners with negative cross resistance. Another useful attribute in a mixing partner would be to possess negative cross-resistance; i.e. where individuals resistant to the vulnerable herbicide are more susceptible to the mixing partner than the wild type. This would actually reduce the frequency of resistant alleles in the weed population as discussed above.

THE RESISTANCE SITUATION

The Situation in Crops Other than Rice

The first verified resistances to evolve were to the triazine herbicides, both along rights of way and orchards, and later in monoherbicide monoculture maize. Over 50 species have evolved resistance worldwide. Areas in Hungary now infested with resistant weeds are so extensive that atrazine cannot be used alone in any maize field. Similarly, there are triazine-resistant infestations in over 2 million hectares of French and German maize, requiring complementary herbicides. In the center of the U.S.A cornbelt there is very little resistance, but there is in surrounding peripheral areas such as Wisconsin, where there is more monoherbicide monoculture of maize, less rotation, and less mixing of atrazine with alachlor than in the corn belt. Triazine resistance has become so common that many cases go unreported. The difference between Hungary and the rest of the maize growing world is telling. Massive maize production began in Hungary later than other countries, but as a monoherbicide monoculture. There was no fast reaction to resistance by the farmers and no rapid switching to other herbicide chemistries that could be effective. Alternatives were unavailable due to government restrictions on importation. This seems to be a similar problem in many lesser developed countries. Of the over the 50 triazine-resistant species only one recently evolved case is clearly due to degradation of atrazine. The rest are target site mutants, having target site cross resistance to all triazines, some phenylureas (but not diuron), uracils and other photosystem II herbicides (LeBaron and Gressel 1982).

Target site resistance evolved to the tubulin-binding herbicide trifluralin in *Eleusine indica* (L.) Gaertner in the U.S. South in cotton (Vaughn *et al.* 1987) and in *Setaria viridis* (L.) P. Beauv. in vast areas of western Canada where it was used in both wheat and oilseed rape for 20 years (Morrison *et al.* 1989). Target site resistance to the highly persistent, soil residual, chlorsulfuron appeared in five species within 3-5 years of use (Reed *et al.* 1989; Saari *et al.* 1992, 1994). The areas currently infested are limited [except in Australia (Powles 1993)] and the manufacturer has taken measures that they hope will delay resistance (McKinley 1990; Reed *et al.* 1989). Many of the resistant biotypes have cross resistance to imidazolinones and other sulfonylureas (Hall and Devine 1990; Saari *et al.* 1992, 1994).

Table 2. Likelihood of evolution of resistance based on persistence characters and targets of herbicides used in rice.

Herbicide	Persistence ^a		Target ^b
	months	t _{1/2} (days)	
a. Herbicides with low likelihood of resistance			
2,4-D	<1(c,e)		UK
Bentazon	1-3(c,e)		PSII
Benzofenap			HPPD?
Bifenox		3-6(n)	Protox
Bromobutide			PM
Butachlor	1-3(c,e)	4-14(e,j)	PM
Chlomethoxynil		5(i)	Protox
Chlornitrofen		15-50(k)	Protox
Dimepiperate		<7(g)	PM
Esprocarb			PM
MCPA	<1(c,e)		PM
MCPB	<1(c)		PM
Mefanacet			UK
Molinate	<1(c)	21(e)	PM
Naproanilide		7(g)	PM
Nitrofen	<1(c),(d)	11-50(k)	Protox
Oxadiazon		90(g)	Protox
Pretilachlor		20-50(g)	PM
Propanil	<1(c)	1(k)	PSII
Pyrazoxyfen		4-15(g)	HPPD?
Pyrazolynate		10-20(g)	HPPD?
Pyributicarb			PM
Quinclorac	3(h)		UK
Thiobencarb	1-3(c)	14-240(e,f)	PM
b. Herbicides with medium likelihood of resistance			
Daimuron		50(g)	PSII
Dimethametryn		150(g)	PSII
Pendimethalin	3-12(c)		Tub
Simetryn		50(m)	PSII
c. Herbicides with high likelihood of resistance			
Bensulfuron-methyl		28-56(e)	ALS
Fenoxaprop-ethyl		5-14(e)	ACCase
Metsulfuron-methyl		7-42(e)	ALS
Pyrazosulfuron			ALS
d. Hard to classify			
Piperophos		70(g)	UK
Quinoclamine			UK

The classification into risk groups is based on intuitive integration of past history of use of the herbicide or members of its chemical group, knowledge of its mode of action (or lack of such knowledge suggesting multiple sites), its persistence, efficacy and use patterns. "Low" does not mean impossible; there are rare examples of resistance to many of the same or related herbicides under monoculture situations.

- a. letter in parenthesis is source. The source is often not for paddy conditions.
A blank means that no data were found in the sources c to h below.
- b. UK - unknown; PSII-photosystem II; PM - probably multiple target sites;
Protox-protoporphorynigen-oxidase; Tub-binds to tubulin, preventing microtubule formation; ALS-acetolactate synthase; ACCase-acetyl CoA carboxylase; HPPD-*p*-hydroxyphenylpyruvate dioxygenase
From Klingman and Ashton (1982).
- c. From Kuwatsuka (1972).
- d. From Anonymous (1989).
- e. according to (c); t1/2 is 14-21 d under aerobic conditions, 6-8 months under anaerobic conditions; according to (k) and (l) 45d in wetland, 28 in dryland.
- g. From Worthing and Hance (1991).
- h. From Thomson (1993).
- i. From Chiang *et al.* (1987).
- j. In fields varies considerably: 9-14d (From Beetsman and Deming (1974); 1d in summer, 10d in winter Taiwan paddy (From Chiang *et al.* 1987).
- k. First number is wetland, paddy, second is dryland soil. (From Matsunaka and Kuwatsuka 1975).
- l. From Chen *et al.* (1976).
- m. From Izawa *et al.* (1981).
- n. From Ohyama and Kuwatsuka (1976)

Paraquat resistance has evolved in three *Conyza* (Syn. *Erigeron*) species as well as *Epilobium ciliatum* Raf., *Poa annua* L., and *Lolium perenne* L. in various places in the world and in other species in Australia (Powles 1993). There are various thoughts on the mode of resistance, which may vary from species to species. There is often a low level cross-resistance to photosystem II and diphenylether-type herbicides (Shaaltiel *et al.* 1988; Clay 1989).

After more than four decades of use, 2,4-D/MCPA resistance has been reported in *Ranunculus acris* L. and *Carduus nutans* L. in New Zealand (Bourdote *et al.* 1989). Recently, 2,4-D resistance appeared in *Sinapis* in monoculture wheat (Hall *et al.* 1993). The most disturbing resistances are those to virtually all selective herbicides used in wheat. *Alopecurus myosuroides* Huds. evolved resistance to chlorotoluron in England and there are new reports yearly of co-evolution in other areas (Moss 1992). *Lolium rigidum* Gaud. has evolved resistance to diclofop-methyl at many sites in four Australian states with millions of hectares affected (Powles 1993). Many of the biotypes of these two weeds have cross-resistance to all other wheat herbicides. In many instances, they never saw these other herbicides. This type of resistance is clearly a threat to wheat growing areas worldwide, and we must learn how to prevent similar cases from evolving. The recent first instances of isoproturon-resistant *Phalaris minor* Retz. in India (Malik and Singh 1993; Singh *et al.* 1993) is disturbing as it was exacerbated by rice. Paddy kills the seed of most of the winter weeds appearing in double-cropped wheat, except for *P. minor*. This heretofore minor weed became the predominant weed in wheat in India, and isoproturon was used for the past 10 years for its control. Rather large pockets (ca. 30 km diameter) have appeared scattered throughout the green revolution wheat/rice areas, and they are expected to expand.

The first cases of multiple resistance have begun to evolve. Both in Hungary (Pölös *et al.* 1988), in England (Moss 1992) and Australia (Powles and Matthews 1992; Powles 1993). Paraquat was used to control triazine-resistant *Conyza canadensis* L. and *Epilobium ciliatum*, and multiple

resistances then evolved. Some of the cases of resistance in Australian *Lolium* are clearly multiple as well as cross resistance (Powles and Matthews 1992; Powles 1993). Such multiple; sequentially evolved resistances are common with insecticides. We can expect more of the same with weeds, especially along treated roadsides where sterilant levels of each herbicide are used until resistance evolves.

Resistance in Rice

2,4-D resistance. In 1980, about 20 years after 2,4-D was first used, farmers in a northern province in the Philippines reported that the broadleaf weed *Sphenoclea zeylanica* Gaertner showed a high degree of tolerance to 2,4-D (Sy and Mercado 1983). Strains of *S. zeylanica* were classified as susceptible, moderately susceptible, and resistant (Migo *et al.* 1986). Susceptible strains were observed in areas with no 2,4-D use while resistant strains were observed in areas with high 2,4-D use (one to two applications per year). Both susceptible and resistant strains had similar levels of injury within 12 days of treatment with 0.5 to 1.0 kg/ha 2,4-D, after which the resistant strain recovered while the susceptible strain died (Mercado *et al.* 1990). The moderately susceptible strain was less responsive to N application than the susceptible strain, and had a thicker cuticle at the 8 to 10 leaf stages, the stages at which this species is most tolerant to 2,4-D (Mercado *et al.* 1990). However, because the weed is susceptible to early application (before 8 to 10 leaf stage), or to 2,4-D formulations containing a surfactant, resistance is only partial.

About nine years later (1989) in Malaysia, the sedge *Fimbristylis miliacea* (L.) M.Vahl was observed to survive 2,4-D treatments in direct-seeded rice fields where 2,4-D was applied one to two times in a season since 1975 (Ho 1992). Resistance to 2,4-D was confirmed at rates 16 times higher than the use rate (Figure 4). Although both resistant and susceptible biotypes were initially injured, the resistant biotype recovered by 2 weeks after treatment. Both biotypes exhibited similar size and form of inflorescence. The resistant biotype was cross-resistant to MCPA but not to propanil, paraquat, or glufosinate (Watanabe *et al.* 1994).

Propanil-resistant *Echinochloa* spp. Propanil, a herbicide affecting photosystem II in a manner similar to triazines and phenylureas, has been widely used in many rice growing areas to control *Echinochloa* and other grass species. *Echinochloa crus-galli* (L.) P. Beauv. in western Greece ceased being controlled by standard rates of propanil (1-4 kg/ha). Initial signs of phytotoxicity appeared for the first week (like the wild type) but plants later recovered after being treated with 8 kg/ha (Giannopolitis and Vassiliou 1989). Propanil had been used continuously for 10 years, and there was a slight difference in extent of resistance between two resistant biotypes.

Similarly, after 30 years of continuous use, propanil-resistant *E. crus-galli* populations were found in rice fields in Arkansas. In late 1980s, farmers observed that *E. crus-galli* in their rice fields survived propanil treatments (Walton and Holmdal 1992). From 1990 to 1992, studies conducted in the greenhouse and in growers' fields containing infestations of the uncontrolled *E. crus-galli* confirmed resistant to 11 kg / ha, three times the use rate (Smith *et al.* 1992; Smith and Baltazar 1993). More recent reports indicate resistance to rates six to eight times higher than recommended (Carey *et al.* 1992b; Anonymous 1993a). A survey conducted to determine the extent of resistance showed that 60 farms in 11 countries in Arkansas had highly resistant biotypes

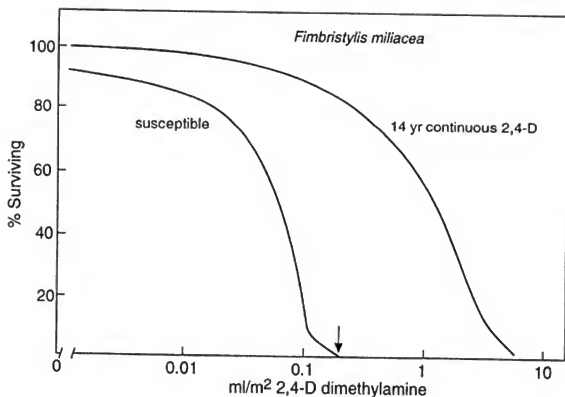


Figure 4. 2,4-D resistance in the sedge *Fimbristylis miliacea*. Soil from rice area treated for 14 years with 2,4-D (compared to an area without putative resistance) was potted, fourteen concentration wetted, and all other germinating species removed. 2,4-D was applied 34 days after puddling, and survival was scored. Curves were fitted to the data points in Watanabe *et al.* (1993).

with only <50% control at 4.5 kg/ha (Carey *et al.* 1992a). Fields with a rotation scheme of 1 yr rice: 2 yr soybean had less resistant biotypes than fields with rotation schemes of 2 yr rice: 2 yr soybean, 1 yr rice: 1 yr soybean or continuous rice (Carey *et al.* 1992a). Alternative grass herbicides that can control resistant *E. crus-galli* are single treatments of quinclorac, thiobencarb, or fenoxaprop, or tank mixtures of propanil with thiobencarb, pendimethalin, or quinclorac. The commercially formulated mixture of propanil + molinate can control it at two-leaf stage but not at later stages (Baltazar and Smith 1994).

After 10 years of continuous use of propanil in Columbia, resistance was reported in *Echinochloa colona* (L.) Link (Fischer *et al.* 1993). Four populations from rice fields treated for ten years were compared with two populations where the fields had been treated discontinuously, and with a pristine, never treated population. The dose response curves split into four statistically ($p < 0.05$) different groups. The discontinuously treated groups had a 30% higher I_{50} than the pristine group and three of the 10 year treated material had a 4.7 fold (average) shift of the I_{50} and one population was 8.6 times more resistant (Figure 5). As with *E. crus-galli*, alternate herbicides can control the *E. colona*, but no dose-response data were presented, so one cannot know if there was a modicum of cross resistance.

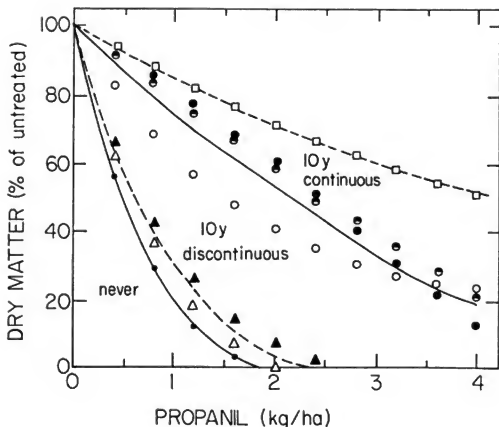


Figure 5. Different levels of propanil resistance in different populations of *Echinochloa colona*. The dose response curves are shown for a pristine (never treated) population (lower solid line); two populations treated discontinuously with propanil that are significantly different from the previous (lower dashed line); three populations treated for 10 years with propanil (upper solid line), significantly different from the previous; one population treated for 10 years (dashed upper line), significantly different from the previous. Source: Statistics from Table 2 and graph redrawn using data in Fischer *et al.* (1993).

By analogy with other species, the best hypothesis is that *Echinochloa* spp. can elevate levels of (an) enzyme(s) that degrade(s) propanil, biochemically mimicking rice. This/these enzyme(s) do not degrade other herbicide chemistries. Preliminary studies by Carey *et al.* (1992a) suggest that metabolism may be responsible for resistance as indicated by the following 1) resistant and susceptible plants were controlled (90%) when propanil was applied following the carbamate insecticide carbaryl. Carbaryl and cholinesterase-inhibiting organophosphate insecticides inhibit propanil arylamidase in rice (Matsunaka 1968); 2) both biotypes appeared to be similarly inhibited by propanil (85%) for the first two weeks after treatment, but the resistant biotype recovered a week later; and 3) extreme rates (>17 kg/ha propanil) can control both resistant and susceptible biotypes, indicating that very high rates may overcome the resistance mechanism (Carey *et al.* 1992a). Subsequent studies by Carey (1994) confirmed that resistant *Echinochloa* hydrolyzed propanil to 3,4-dichloroaniline and sugar conjugates in a manner similar to rice; hydrolysis did not occur in susceptible *Echinochloa*. There were no differences at the active site absorption, or translocation between resistant and susceptible biotypes.

Propanil-resistant *E. crus-galli* has also been found in rice fields near Tarragona, Spain. Recent preliminary experiments showed that the most resistant biotype degraded over three times more

propanil in 2 days than the wild type, leaving less than a quarter of the parent herbicide (DePrado and Lopez-Martinez, unpubl.).

Mimicry does not require that the same propanil aryl-acylamidase as rice be used. Another pathway could be involved and this should be investigated for practical reasons to find a way to prevent resistance due to enhanced metabolism. Then, it is possible that another chemical, including some alternative herbicides could act as synergists, blocking this metabolism, allowing for the continued use of this cost-effective herbicide.

The data above suggest that it is doubtful if any of these cases are due to a modification of the photosystem II target site, as has been found with many weeds, including populations of *Echinochloa* (cf. Gressel *et al.* 1982). Photosystem II resistance is characterized by an immediate resistance that is of a large increment (100-1000 fold shift in I_{50}). Non-target site resistance is not a new phenomenon with *Echinochloa*. Populations of *E. crus-galli* evolved enhanced levels of resistance to triazines in France (cf. Tables 3.1 and 3.6 in Gressel *et al.* 1982). After 14 years of treatment, with atrazine in continuous maize, 35% of a population was unaffected by 5 kg/ha. Other *Echinochloa* populations evolved plastid level resistance to much higher levels of atrazine.

Resistance to inhibitors of acetolactate synthase (ALS). Herbicides belonging to this group are among the fastest selectors of resistance known. This is because of a high natural mutation frequency to resistance on the gene for the target site, and high selection pressure due to exceedingly high persistence of the first released inhibitors of this key enzyme.

There is a possibility that a goodly number of resistant individuals were in rice fields even before these herbicides were used in rice, due to use of ALS inhibitors along irrigation ditchbanks and roadways. Indeed, the use of imazapyr along ditchbanks of rice fields in Costa-Rica selected for resistance in *Ixophorus unisetus* (Valverde *et al.* 1993). Interestingly, in this case most of the resistant biotypes were negatively cross resistant to the one sulfonylurea herbicides tested (sulfometuron-methyl).

One of the causes of lowered selection pressure is unequal distribution of a herbicide after spraying. As diffusion in water is much faster than diffusion in soil, spraying flooded rice paddies should even out the distribution of herbicides and increase the selection pressure by assuring that every susceptible individual comes in contact with the herbicide and is killed. Thus, it was no surprise that in the third year of widespread use of bensulfuron-methyl, four of the 2000 California rice growers reported stands of two resistant weeds; *Sagittaria montevidensis* Cham. & Schltdl. and *Cyperus difformis* L. (Pappas -Fader *et al.* 1993,1994). The I_{50} for the resistant *Sagittaria* increased 600 fold and that for *Cyperus*, 30 to 300 fold in different biotypes. The resistance was traced in both species to an insensitive target enzyme. The following year 100 growers reported resistance problems (and probably others failed to report them), both in the above two species and in *Scirpus mucronatus* L. and *Ammannia coccinea* Rottb.. This exacerbates a problem situation in California where few herbicides are allowable, as the water from the paddies ends up in drinking water. Some thiocarbamate herbicides are detectable organoleptically at concentrations too low for instrumental detection.

Similarly bensulfuron-methyl resistance appeared in Australian rice fields three to six years after continuous use. In 1993, biotypes of *Cyperus difformis* resistant to two to four times the

recommended rate was subsequently confirmed (Graham *et al.* 1994). Two other species, *Sagittaria montevidensis* and *Damasonium minus* (R.Br.) Buchenau also showed signs of evolving resistance to bensulfuron-methyl.

It is doubtful whether ALS-inhibiting herbicides can be used alone (or in a mixture where the mixing partner has no effect on some weed species) for more than five years running in any rice growing situation, without problems of resistance. There is a good possibility that a mixing partner that has some inhibiting effect on a weed controlled by an ALS inhibitor will greatly increase the duration until resistant populations are evident.

Butachlor. Butachlor-resistant *Echinochloa crus-galli* appeared in China after 30 years of use (Huang and Lin 1993). *E. crus-galli* evolved resistance to butachlor when butachlor was used for more than 8 years (Figure 6). Resistance also correlated with cropping season; i.e., there was greater resistance with two rice crops per year than in one rice crop alternated with two rice crops, or when there was only one rice crop per year, with butachlor used each time rice was grown.

Other cases. Biotypes of *Echinochloa crus-galli* resistant to quinclorac and others resistant to molinate have been found near Sevilla and Tarragona, respectively in Spain (De Prado and Lopez-Martinez, unpublished data). Five resistant *Echinochloa* populations appeared in the first year of quinclorac use in southern Spain, but not in other rice growing areas. The level of resistance is variable, but the weeds were resistant to higher than the recommended rates (Figure 7). The phenomenology of immediate resistance has caused the researchers to look in to the possibility that the resistant populations might be in a separate species or sub-species of *Echinochloa*. Conversely, they could belong to populations that had been selected for resistance to some other xenobiotic, and they are cross-resistant to quinclorac.

HERBICIDE USE PATTERNS IN RICE

So far, there are only a few cases of herbicide resistance in rice, one of the most widely grown crops in the world. Why are there so many more cases of herbicide resistance in maize, wheat, orchards and roadsides than in rice? It is only when we analyze herbicide use in rice, the mixtures used and the rotations, and compare them with the criteria defining the rapidity of evolution, can we partially answer the question about why resistance is so rare in rice.

Flooding defines the weed flora of much of the rice cultivated; only those weeds adapted to this special agroecosystem can exist. The establishment method (transplant or seeded, dry or wet-seeded) largely affects the weed spectrum as do herbicide efficacy/selectivity; and consequently the kind and degree of herbicide use. Grasses, predominantly *Echinochloa* spp. are usually the first species that emerge and grow with rice at the beginning of the season. Broadleaf weeds and sedges grow towards the middle to latter part. Thus, all three kinds of weeds grasses, broadleaf weeds, sedges pose problems that must be controlled at different times in the course of a growing season.

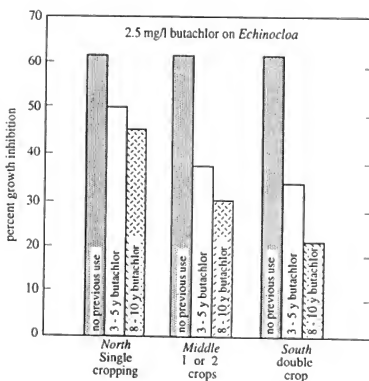


Figure 6. Appearance of *Echinochloa crus-galli* resistant to butachlor. The magnitude of resistance is a function of both the total number of treatments treated as well as the number of treatments per year. Source: Redrawn from Huang and Lin (1993).

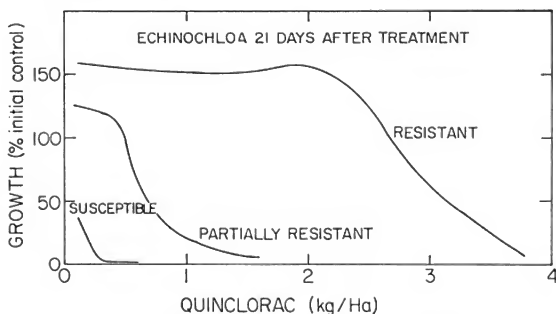


Figure 7. Different levels of quinclorac resistance in different populations of *Echinochloa crus-galli*. The weight reduction of the treated plants was related to the weight increase of untreated plants during the three weeks following treatment to final measurement. Drawn from unpublished data kindly provided by DePrado and Lopez-Martinez.

Pre-emergence herbicides (2 days before seeding or transplanting to 8 days after seeding/transplanting) are mainly used for control of fast germinating annual grass weeds in rice. Early post-emergence treatments (8 to 20 days after transplanting/seeding) control annual grasses and/or broadleaf weeds and sedges. Late post-emergence treatments (20 to 30 days after seeding/transplanting) control mostly annual broadleaf weeds or sedges.

Phenoxy herbicides (which have auxin activity at low concentrations), were the first group of herbicides used, beginning in the mid 1940s. The second group (chloroacetamides, thiocarbamates, dinitroanilines, diphenylethers) were developed and used since the 1960s and 1970s. In 1980s new compounds including sulfonylureas, aryloxy-phenoxypropionates, and others like quinclorac, mefenacet, pyrazoxyfen, etc. were introduced. Herbicides developed since the 1980s have wider application windows and are applied any time from pre-emergence to early post-emergence (i.e. quinclorac) or from early to late post-emergence (i.e. sulfonylureas). These newer compounds also have lower use rates, new chemistries, and new modes of action compared with the older compounds. The pre-emergence treatments do not last through the cropping season and they control mainly grass weeds. Thus, mixtures or sequential applications of a pre-emergence followed by post-emergence herbicides are often used.

The kind and number of herbicides and/or herbicide mixtures and applications, the degree of use (percent area treated) vary among the rice-growing countries. The following discussions will highlight specific herbicide uses and trends in weed response that can lead to changing weed spectra as well as evolution of resistance in selected rice-growing areas in the world. The patterns of herbicide use are often a function of the economic development of user countries and the availability of herbicides, which are often imported. The patterns vary from multiple applications and mixtures, to single herbicides, nationwide.

Patterns in Highly Developed - High Herbicide Use Countries

U.S.A. The total rice-growing area in the U.S.A. is 1.1 M ha. In the world it ranks only 17th in terms of rice area but is the 4th highest yield producer (Anonymous 1993b). Rice is generally grown as a monoculture except where red rice is a problem. Then rice is followed by two years of soybeans and /or grain sorghum (Smith 1989a).

The U.S.A. is one of the heaviest herbicide users in rice. Since the 1970s, almost every hectare of U. S. rice received one herbicide treatment/ha for grass control, while 80% received a second treatment for broadleaf and/or sedge control (Smith and Hill 1990; Hill and Hawkins 1994). At least one treatment is for *Echinochloa crus-galli*, *Leptochloa panicoides*, or *L. fascicularis* (Lam.) Gray control. Where grass reinfestations occur or where broadleaf, sedge or hard-to-control species occur, as many as four treatments are applied; two in early season and two in midseason (Smith 1989b).

There are 10 single herbicides and 10 herbicide combinations (mostly tank mixtures) used for control of weeds in rice in the U.S.A. four for grass control (molinate, thiobencarb, propanil, pendimethalin and fenoxaprop) and five for broadleaf/sedge control (acifluorfen, bentazon, bensulfuron-methyl, 2,4-D and MCPA) (Anonymous 1992). There are eight herbicide mixtures for broad-spectrum control having propanil as the principal component in a tank-mix or in sequential application with the grass compounds (molinate, pendimethalin, thiobencarb or fenoxaprop) or with broadleaf or sedge controlling compounds (acifluorfen, bensulfuron-methyl,

etc.) to increase weed spectrum and residual activity, as propanil has no residual activity (Smith 1989b; Smith and Hill 1990).

Propanil became a mainstay after introduction in southern U.S.A. and California in 1962. Its use in southern U.S.A. increased steadily from 15% in 1962, 80% in 1974 (Smith *et al.* 1977) to practically every hectare (80 to 95%) of southern U.S.A. rice areas by 1990s (Smith and Hill 1990). About 3.4 to 5.6 kg/ha propanil are applied to one to four-leaf *E. crus-galli* during the first 15 to 30 days of rice growth. When reinfestations occur, a second application is made to 70% of rice in the southern U. S. (Smith and Hill 1990). If the second application is propanil, then a total of 6 to 11 kg/ha are applied per hectare per year. Propanil has no residual activity, it is ineffective against germinating or unemerged grasses or those that are larger than the four-leaf stage (Smith *et al.* 1977). Thiocarbamate and dinitroaniline herbicides with residual activity are used to control *E. crus-galli* that emerges one to three weeks after application. Molinate controls *E. crus-galli* that germinates for the first few days after application. However, if *E. crus-galli* germinates over a long period of several weeks, escaping early application of herbicides, two applications of propanil plus one application of molinate may be needed (Smith 1989b).

The success of propanil as an effective rice herbicide is largely due to its excellent selectivity between rice and grass weeds based on differential metabolism (Frear and Still 1968; Still 1968a; Yih *et al.* 1968a, b). Metabolic selectivity between emerged rice and grasses is due to the existence of an arylacylamine amidohydrolase in rice. While both rice and grasses absorb and translocate propanil rapidly and equally to the leaves (Yih *et al.* 1968a), this enzyme rapidly detoxifies propanil by oxidative metabolism and hydrolysis (Frear and Still 1968), and b-oxidation (Still 1968b). Young rice leaves contain approximately 60-fold greater arylacylamidase than young *E. crus galli* leaves, while roots of both plants contain the same low concentration of the enzyme (Frear and Still 1968). Arylacylamidase activity in 23 rice species has been directly correlated with the level of resistances to propanil (Chen and Matsunaka 1989; Matsunaka and Aoyama 1981). The biosynthesis of this enzyme in rice is under the control of a single dominant gene (Matsunaka 1974).

The two new grass herbicides, quinclorac and fenoxaprop provide excellent (90 to 95%) control of propanil-resistant or susceptible *Echinochloa crus-galli*. Fenoxaprop is also one of the few grass herbicides that provides excellent control of *Leptochloa* spp., grasses which dominate once *E. crus-galli* is controlled within a cropping season. However, caution must be observed with use of fenoxaprop; it has rapidly selected for evolution of resistance in many grass weeds.

Quinclorac was approved for use in 1993 in certain areas in the southern U.S.A. to control propanil-resistant *Echinochloa crus-galli* and other grasses and some broadleaf weeds; however it does not control *Leptochloa* spp. (Anonymous 1993a). There is also one report of resistance to quinclorac in *Echinochloa* in Spain.

In 1988, California rice areas received 2.6 herbicide treatments per hectare every year. From 1990 to the present, there were only 1.8 - 2 treatments/ha every year (Hill and Hawkins 1994). In California, environmental restrictions allow only five herbicides for rice: molinate, thiobencarb, propanil, phenoxys (2,4-D and MCPA) and bensulfuron-methyl (Hill and Hawkins 1994). The changes in use are depicted in Figure 8. Furthermore, because of drift problems with

phenoxy and propanil, well-water problems with bentazon and thiobencarb, these were either restricted or

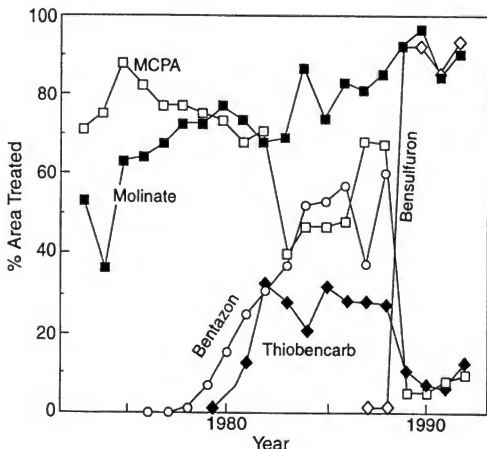


Figure 8. Changes in herbicide usage in California rice. Note immediate adoption of bensulfuron-methyl in 1988, at the expense of MCPA, bentazon and thiobencarb. Redrawn from data kindly provided by Lyndon Hawkins.

de-registered for use in California rice leaving only molinate for grass control and bensulfuron-methyl for broadleaf and sedge control (Hill and Hawkins 1994).

Bensulfuron-methyl was introduced in California in 1989 for control of broadleaf and sedge weeds (Hill *et al.* 1990) and was rapidly adopted (Figure 8). It is more selective in rice than 2,4-D, has no perceived environmental problems in water (unlike bentazon), and can be applied at earlier growth stages than phenoxy or bentazon. Nearly 100% of California rice has been treated with bensulfuron-methyl since 1989 (Hill *et al.* 1994; Hill and Hawkins 1994). Thus, it is not hard to understand why resistance evolved so quickly. Only the phenoxy (2,4-D, MCPA) remain available as alternatives; thiobencarb controls *Cyperus difformis*, one of the resistant species. Alternative cultural practices and herbicides with different mechanisms of action will be needed to control these species.

Japan. The total rice area in Japan is about 2.1 M ha. Most of the rice fields have been treated with at least two herbicide treatments/ha per season since 1975 (Matsunaka 1987). Since 1982, 64% of the rice fields received two treatments/ha/season, 19% received 3 to 4

treatments/ha/season, while 18% received at least one treatment/ha/season (Matsunaka 1987), totalling 177% treated ha (Shibayama 1994).

The herbicides used in Japan for rice weed control are almost all granular formulated products developed mainly for transplanted, irrigated rice. Before the 1980s, the use of two to three sequential applications of different herbicides was the main practice to control the whole spectrum of grasses, broadleaf weeds and sedges that infest rice during the season. These applications are made at any of the following stages: 1) early treatment or just after transplanting mainly for grass control; 2) middle treatment applied 10 to 14 days after transplanting to control grasses and certain broadleaf weeds and sedges; and 3) late treatment at 20-30 days after transplanting to control mainly broadleaf weeds and sedges. In the 1980s, "one-shot" mixtures of two or three herbicides for use once in the season were introduced. They are widely used for their broad weed spectrum and long residual activity (Matsunaka 1987) and to save on labor expenses (Shibayama 1994). One-shot treatments are applied either at pre emergence (soil applications) or at early post emergence (foliar applications).

The first herbicides used in Japan were phenoxy in the 1950s. In late 1950s, pentachlorophenol was introduced for control of grasses but was discontinued due to fish toxicity. In 1960s to 1970s diphenylethers (nitrofen, chlornitrofen) were used as early stage treatment for grass control followed by simetryn and thiobencarb or molinate for middle stage treatment to control broadleaves and sedges. In 1970s thiocarbamates (thiobencarb and molinate), butachlor, chlomethoxynil, oxadiazon, piperophos, dimethametryn, and pyrazolynate were introduced (Matsunaka 1987). Bentazon was introduced in 1975 for perennial broadleaf weeds and sedges and the use of phenoxy decreased. Butachlor use started in 1973 and peaked in 1984 for annual grass control and some perennials (e.g. *Scirpus juncoides* Roxb.). In 1984 pretilachlor, another chloroacetamide was introduced also for annual grass control but it also controls some broad leaf weeds. The following herbicides have been introduced since 1987: pyrazoxyfen, benzofenap, dimepiperate, isopropylate, pyrazosulfuron, mefenacet, bromobutide, and chlornecprop (Matsunaka 1987).

Since 1983 there are about 12 single herbicides and 23 herbicide combinations, a total of 35 herbicides and mixtures used for transplant rice weed control (Table 3). The use of single herbicides (chloracetamides, thiocarbamates, diphenylethers, phenoxy) declined; the fastest rate of decrease occurred in 1987. To date, only about 11% of rice area is treated with single herbicides. Treatment combinations and one-shot treatments have increased steadily since 1983, with fastest rate of increase in 1987. In 1991, 84% of the total rice area was treated with one-shot treatments; this further increased to 89% in 1993 (Shibayama 1994). A very popular one-shot treatment combination is a sulfonyleurea (bensulfuron-methyl or pyrazosulfuron) combined with thiobencarb, dimepiperate, or isopropylate. Rice is resistant to bensulfuron-methyl because it detoxifies this compound by *O*-demethylation on the pyrimidine ring, probably by a monooxygenase. This detoxification is enhanced by a mixture with thiocarbamates; thus, thiocarbamates provide a safening effect on the rice plant (Matsunaka 1987). In addition, this combination broadens the weed spectrum, as thiocarbamates are mainly grass-active compounds while sulfonyleureas are mainly against broadleaf and sedge weeds.

Before herbicides were used, hand and mechanical weeding were the only direct weed control methods. *Echinochloa oryzicola* and *Monochoria vaginalis* (Burman f.) Kunth were the dominant weeds. After introduction of phenoxy (2,4-D and MCPA) in the 1950s for annual

broadleaf and sedge control, *E. oryzicola* became dominant. In the 1960s, pentachlorophenol, nitrofen, and chlornitrofen were used against *E. oryzicola* and other annual weeds but a perennial

Table 3. Herbicide use in rice in Japan.

Herbicide	Area treated (1000ha)	Herbicide	Area treated (1000ha)
SEQUENTIAL TREATMENTS		ONE-SHOT TREATMENTS	
Pre-plant (pre-emergence)		One-shot pre-emergence	
Oxadiazon	61	Bensulfuron-methyl + dimepiperate	68
Oxadiazon + butachlor	194	Bensulfuron-methyl + pretilachlor	59
Soil applied (pre-emergence)		Bensulfuron-methyl + thiobencarb + mefenacet	491
Butachlor	76	Pyrazolynate + butachlor	76
Chlomethoxyfen	85	Pyrazolynate + pretilachlor + dimethametryn	27
Chlornitrofen	266	Pyrazosulfuron + pretilachlor	19
Chlornitrofen + daimuron	101	Pyrazoxyfen + pretilachlor	23
Pretilachlor	93	Pyrobuticarb + bromobutide + benzofenap	43
Thiobencarb + chlornitrofen	33	One-shot early post-emergence	
Foliar or soil-applied (pre-emergence or post-emergence)		Bensulfuron-methyl + esprocarb	229
Bentazon	36	Bensulfuron-methyl + mefenacet + daimuron	510
MCPA-thioethyl + simetryn + dimethametryn	16	Naproanilide + bromobutide + mefenacet	32
Molinate + simetryn + MCPB	153	Pyrazosulfuron + mefenacet	219
Piperophos + dimethametryn	19	Pyrazosulfuron + esprocarb	59
Thiobencarb + simetryn	36		
Thiobencarb + simetryn + MCPB	74		
Foliar applied (post-emergence)			
Quinoclamine	26		
2,4-D	98		
MCPA	112		
Propanil	11		
Bentazon + 2,4-D or MCPA	19		

Source: Anonymous (1993c); Shibayama (1994)

sedge, *Eleocharis acicularis* (L.) Roemer & Schultes, became dominant. In the 1970s, thiobencarb, simetryn, and molinate were used for control of *Eleocharis* and other annual weeds. This resulted in increase of a perennial broadleaf, *Sagittaria pygmaea* Miq. and the perennial sedges, *Scirpus juncoides* and *Cyperus serotinus* Rottb., which became the dominant species in the 1980s. One-shot treatments consisting of combinations of sulfonylureas (bensulfuron-methyl, pyrazosulfuron) for broadleaf and sedge control plus a grass compound (i.e. pyrazolynate, butachlor, thiobencarb, pretilachlor, mefenacet, esprocarb) were introduced for both annual and perennial grasses, broadleaf weeds and sedges. In the late 1980s the dominant species shifted to another perennial broadleaf, *Sagittaria trifolia* L. and a perennial sedge, *Eleocharis kuroguwai* Ohwi, which are both naturally resistant to all existing herbicides. One-shot herbicide treatments have dominated since the start of the 1990s. Annual broadleaf weeds and sedges are also increasing in dominance (Matsunaka 1987; Shibayama 1994).

To date, there is but one report of a weed evolving resistance to herbicides in rice in Japan. A case of *Echinochloa colona* resistant to propanil was found in 1986 (LeBaron and McFarland 1990). Clearly, this has not become a major problem as there are not yet any primary publications on this or further incidents.

Republic of Korea. Korea is one of the most intensive users of rice herbicides in Asia. Although there was very minimal herbicide use for rice weed control before 1966, use of herbicides picked up and increased steadily since late 1960s. In 1977, 65% of the total rice area was treated with herbicides (Kim 1981). This increased to 115% in 1981, 130% in 1986 and and to 142% in 1991 (Kim 1994). Currently, 140% of the total rice area is treated with herbicides, indicating that some areas receive two treatments/ha in a growing season. The first herbicides used in the mid-60s were the phenoxys (2,4-D, MCPA) and pentachlorophenol. In 1970, butachlor, propanil, thiocarbamates (thiobencarb, molinate) and diphenylethers were introduced. The chloroacetamide butachlor was the leading herbicide used since 1970s and had 80% of the market until the mid-1980s (Table 4). In late 1980s, the use of single treatments like butachlor decreased. By 1991, the area treated with butachlor decreased to 36% of total rice area. From late 1980s into 1990s, new compounds like sulfonylureas were introduced, and use of mixtures of sulfonylureas with old or new compounds increased from 3.5% in 1981 to 79% of total rice area in 1991 (Kim 1994).

From only two mixtures in 1981, there are now 13 mixtures used. Two of the main components in these mixtures are sulfonylureas (bensulfuron-methyl or pyrazosulfuron). The most popular of these are butachlor + bensulfuron (23% of treated area), butachlor + pyrazolynate (12%), butachlor + chlomethoxyfen (5.8%), bensulfuron + mefenacet (5.5%), and pyrazosulfuron + butachlor (5.1%) (Table 4). Thus, butachlor is still the most popular among the grass herbicides used, albeit now in mixtures (Table 4).

Weed shifts/tolerance due to herbicides. There are yet no reports of weeds evolving resistance to rice herbicides in Korea, despite intensive use since the 1970s. However, shifts in dominant species have occurred in response to herbicide use. Before herbicides were used in the mid-1960s, the dominant species were the annuals *Echinochloa crus-galli* and *Monochoria vaginalis*. After continuous use of single treatments of chloroacetamides, thiocarbamates, diphenylethers, and phenoxys for control of annual species from mid-1960s to 1980s, perennials increased in weed populations and constituted 54% of dominant species in the 1980s. From the 1980s to the

Table 4. Changes in herbicide use in rice in Korea¹

Herbicide	Treated area ² (%)	Herbicide mixture	Treated area (%)
1981			
Butachlor	82.8	Piperphos + dimethametryn	3.2
Thiobencarb	10.9	Molinate + simetryn	0.3
Pretilachlor	2.5		
Oxadiazon	1.9		
Nitrofen	5.2		
	103.8		3.5
1986			
Butachlor	80.0	Butachlor + chlomethoxyfen	4.7
Thiobencarb	4.5	Butachlor + pyrazolynate	8.1
Pretilachlor	5.2	Piperophos + dimethametryn	2.7
Oxadiazon	4.9	Molinate + simetryn	2.3
Chlomethoxyfen	2.0	Thiobencarb + naproanilide	1.3
Bifenox	1.2	Pretilachlor + naproanilide	1.2
Chlornitrofen	1.1		
	101.7		23.6
1991			
Bentazon	7.8	Mefenacet + bensulfuron-methyl	5.5
Butachlor	35.6	Butachlor + chlomethoxyfen	5.8
Thiobencarb	2.0	Butachlor + pyrazolynate	12.4
Pretilachlor	6.9	Butachlor + bensulfuron-methyl	23.2
Oxadiazon	5.4	Quinclorac + bensulfuron-methyl	2.8
		Pretilachlor + bensulfuron-methyl	4.7
		Molinate + pyrazosulfuron	3.3
		Thiobencarb + pyrazosulfuron	3.2
		Butachlor + pyrazosulfuron	5.1
		Quinclorac + bentazon	2.6
		Quinclorac + pyrazosulfuron	1.0
		Thiobencarb + bensulfuron-methyl	2.4
		Dithiopyr + bensulfuron-methyl	0.3
		Mefenacet + bensulfuron-methyl + daimuron	2.6
	58.3		76.4

Source: Kim (1994)

¹ Does not include use of other herbicides which was 7.5% of treated area in 1981 and 4.6% in 1986, consisting mainly of bentazon, and other unspecified herbicides.

² A sum of more than 100% of area treated indicates that some areas were treated two times.

present, the use of single treatments decreased and herbicide mixtures increased, mainly for control of perennial species. In the 1990s, dominant species still consisted of 60% perennials

and the rest were annuals. The perennial species include *Sagittaria trifolia*, *Sagittaria pygmaea*, *Eleocharis kuroguwai*, *Potamogeton distinctus* A.Bennett, *Scirpus juncoides*, *Cyperus serotinus*, and *Rotala indica* (Willd.) Koehne. Interestingly, despite the continuous use of treatments for control of annuals, *E. crus-galli* and *M. vaginalis* are still dominant. Similar to Japan, the perennials *Eleocharis kuroguwai* and *Sagittaria trifolia* are considered the most difficult to control weeds because the weeds germinate much later than other species, escaping pre-emergence or early treatments (Kim 1994).

Areas with Intermediate Use Patterns

China and India typify developing countries with disparate use patterns within the countries. In the more advanced, intensively cultivated rice areas in both countries, large amounts of (typically older) herbicides are used. In other areas, herbicides are not used, despite weed problems.

China. Herbicide use in rice started in late 1950s with nitrofen and pentachlorophenol for annual grass control (Li and Peizhen 1994; Zhang 1992). In 1974, the area treated with herbicides was about 2.7 M ha. This increased to about 10 M ha in 1991, which is about 35% of the total rice area, and is expected to increase by 1 M ha every year. Zhang (1992) estimates that by the late 1990s, herbicides will be applied to more than 60% of the total rice area. In some major rice regions, herbicides are treated to all the paddy fields, twice in a cropping season (Zhang 1992).

The principal herbicides used for the last thirty years or so are nitrofen, propanil, butachlor, thiobencarb, molinate and oxadiazon; all mainly for annual grass control (Zhang 1992), while MCPA is widely used for control of annual broadleaf weeds and sedges. In 1992, use of MCPA decreased while bentazon or bensulfuron-methyl use increased (Zhang 1992). Newer compounds used since 1990s also include quinclorac, which has excellent activity against *E. crus-galli* and moderate activity against *Monochoria vaginalis*. Quinclorac tank-mixed with bensulfuron-methyl is a recently introduced "one-shot" treatment applied from pre-emergence to mid-post-emergence for control of *E. crus-galli* and *M. vaginalis*. Daimuron applied pre-plant incorporated is used to control the perennials *Scirpus planiculmis* Fr. Schmidt while diuron or prometryn applied post-emergence are used against *Potamogeton distinctus* (Zhang 1992).

There has been no other evolution of resistance in China other than to butachlor. However, weed shifts in response to herbicide use have been observed. Before herbicides were used, the prevalent weeds were mostly annual grasses. Continuous use of herbicides for control of annual grasses shifted the dominant species from grasses to broadleaves or sedges and from annuals to perennials such as *Sagittaria pygmaea*, *Sagittaria sagittifolia* L., *Scirpus planiculmis* and *Potamogeton distinctus* (Zhang 1992).

Taiwan. Herbicides were used since the late 1960s in the 430,000 ha, mainly transplanted rice (Chiang 1992). By the end of 1970s and to the present, practically all rice areas were treated with herbicides (Chen and Wang 1985; Chiang 1981). Butachlor is the most widely used herbicide since the 1970s (Chiang 1992). In 1991, butachlor, applied alone was used on 47% of the total rice area while butachlor applied in tank mixtures with other herbicides was used on another 35% of the total rice area. The percent area treated with butachlor mixtures are as follows: butachlor + chlomethoxylin (18%), + bensulfuron-methyl (6%), + oxadiazon (5%), + chlornitrofen (4%), and + daimuron (2%). The rest of the rice area is treated with

pyrazosulfuron (5% of total rice area), oxadiazon (3%), chlornitrofen (2%), bentazon (4%), and others (8%) (Chiang 1992).

Butachlor applied pre-emergence or shortly before or after transplanting /seeding controls most annual grasses especially *E. crus-galli*. It is most active when applied from germination to one-leaf stage and is less effective on less susceptible species like *M. vaginalis* and *Scirpus juncoides* if applied at later stages (Chiang 1992). Bentazon is applied to 4% of total rice area for control of perennial broadleaf weeds and the sedges *Sagittaria trifolia* and *S. pygmaea*. Phenoxys (2,4-D and MCPA) are seldom used. In the 1990s, the use of sulfonylureas (bensulfuron-methyl and pyrazosulfuron) is increasing because of their wider application windows, which is from pre-emergence to mid-or late post-emergence (Chiang 1992).

India. The total area treated with herbicides was 2.7 M ha in 1989 (26% of the developed rice area) and increased to 3.7 M ha (36% of developed area) by 1994 (Anonymous 1994a). About 55 to 65% of these areas are found in the north where irrigated transplanted rice is the main crop; mainly in Punjab, Haryana, western Uttar Pradesh, and smaller areas in Jammu, Kashmir, Tamil Nadu, and Andhra Pradesh. In the remaining 35 to 45% herbicide-treated areas, 19-23% is in the east zone, 15-20% in south, and 1-2% in west zones. Herbicide use is not common in rainfed rice or in the rice areas of northeast and south India. 2,4-D is used for broadleaf control where needed, and 1000-1500 tons of butachlor are used for grass control, with a third as much in thiobencarb and anilophos, with use of the latter increasing and the former decreasing (Sabrawal and Rath 1993). Many areas in the green revolution rice districts have used butachlor repeatedly year after year.

Areas with Extensive Herbicide Use

Data on use patterns are hard to obtain for these areas, and the variability of use is great. In each one of these developing countries there are some areas of more intensive, high input agriculture and more areas of low input.

The use patterns are similar in these countries; the general trend is towards greater use of herbicides in irrigated, transplanted rice than in rainfed, direct-seeded rice. However, more intensive use (per unit area) is expected (and already observed) in wet-seeded areas where the absence of crop rows in broadcast pregerminated rice makes cultural control methods expensive as well as inefficient, and leaving chemical control as the best alternative. Very little or no herbicide is used in dryland rice. The greatest herbicide use is probably in Malaysia, Thailand, and possibly the Philippines and Sri Lanka; while lesser use is observed elsewhere.

The continuous use of herbicides for control of annual grasses and broadleaf/sedge weeds results in a shift of dominant species from annuals (*E. crus-galli*, *M. vaginalis*) to perennials like *Paspalum distichum* L., *Scirpus maritimus* L. and *Pistia stratiotes* L. in certain southeast Asian countries (Kim and De Datta 1974; De Datta 1977, 1981).

The dominant weed problems in Latin America are red rice, *Echinochloa colona*, *E. crus-galli*, and certain sedges (Labrada 1992). *E. colona* is found in almost all of these countries. *E. crus-galli* and *E. crus-pavonis* (Kunth) Schult. are not found in Central America, but are the major species in Caribbean and South American countries. Populations of *Ischaemum rugosum* Salisb. (a perennial grass), are increasing in almost all Caribbean, Central America and South American countries because this weed emerges much later after rice emergence and escapes early herbicide

treatments (Aguero 1985). In irrigated areas, *Eichhornia crassipes* (Martius) Solms-Laub. is increasing in dominance (Labrada 1992).

Thailand. The area treated with herbicides is 10 to 20% in transplanted rice which constitutes 60% of the rice area, 80% in wet-seeded rice (15% of area), less than 10% in deepwater rice and none in dryland rice (DeDatta 1989). Handweeding once or twice in a season is the common practice, especially in transplanted rice (25% of area). Thus, only a small (but high yielding) proportion of Thai rice is heavily exposed to herbicide use.

The most widely used herbicides (from highest to lowest) are: 2,4-D, butachlor, pretilachlor, thiobencarb, propanil, propanil + molinate, fenoxaprop, bensulfuron, oxadiazon, pendimethalin, 2,4-D + propanil, quinclorac, piperophos + dimethametryn, metsulfuron-methyl, and molinate. The use of quinclorac, fenoxaprop, bensulfuron-methyl and metsulfuron-methyl has been increasing since 1989 (Vongsaroj 1992; Anonymous 1994b).

Philippines. In 1980, about 1.2 M ha of rice areas were treated with herbicides in the wet season (40% of rice area) while 0.8 M ha (20%) were treated with herbicides in the dry season (De Datta 1980). Based on herbicide sales reports from 1987 to 1989, the area treated with herbicides to date is still estimated to be 1.2 M ha (Cruz 1990). Herbicides used in the Philippines include 2,4-D, butachlor and pretilachlor as most widely used; also MCPA, oxadiazon, thiobencarb, propanil, bentazon, pendimethalin, oxyfluorfen, bensulfuron-methyl, and commercial mixtures of 2,4-D with either butachlor, piperophos, or thiobencarb (Cruz 1990).

Malaysia. From the 1970s to 1980s, there was only limited use of rice herbicides (Saharan 1977; De Datta 1980). From the 1980s, 2,4-D was the major herbicide used; it was applied once or twice by most farmers in direct-seeded rice and also in transplanted rice. Herbicide importation data from the Muda Agricultural Development Authority reported that of the three herbicides imported (2,4-D, MCPA, paraquat), 94% was for 2,4-D, which was used in the Muda irrigated rice schemes in 1980 (Baki and Azmi 1992). In 1983, the amount of 2,4-D decreased to 71% and to 34% in 1988. During the same period, the use of molinate increased from 3 to 32% (of total amount imported), thiobencarb from 0 to 4%, propanil from 0 to 2%, and others (oxadiazon, MCPA, propanil + molinate) from 0 to 2%. Paraquat (26%) is also still widely used (Baki and Azmi 1992).

Sri Lanka. Twenty-five percent of the rice area is transplanted, 70% is wet-seeded, while 1 to 5% is dry-seeded. Of these, 63% is irrigated rice while 29% is rainfed. In transplanted rice, 10 to 100% of rice area in different areas is treated with herbicides. In broadcast-seeded (wet-seeded) rice, handweeding or mechanical weeding is expensive and inefficient, thus, 90 to 100% of these areas are treated with herbicides. No herbicides are used in dry-seeded or dryland rice (De Datta 1989). MCPA, 2,4-D, propanil and butachlor are most widely used.

PROGNOSES FOR RESISTANCE

The previous sections have described the factors controlling herbicide resistances in weeds and described how these interacted to bring about resistant populations of weeds, mainly in other crops, but also in rice. Could those few cases that evolved in rice have been prevented? How? What rice herbicides are at risk from further resistance and which common rice weeds are the ones most likely to evolve resistance? We try below to integrate all this previous information

to try to answer these questions. We will do so by chemical group, and a bottom line summary is found in Table 2. The decisions for placement in risk categories are based on past histories with given chemistries and target sites, the herbicide persistence, efficacy on weeds not controlled by mixing partners, selection pressure, etc. It is surprising how much less information is published on the site of action and even persistence of rice herbicides compared to herbicides used for other crops. The least available information is for herbicides not registered for use in the U.S.A., which does lead to questions. One wild card in our prognostication is the inability to estimate whether a weed has the genetic capacity to evolve metabolic resistance that will allow it to degrade the herbicide. It may seem daunting or promising, depending on outlook that we have placed some rice herbicides with verified resistance in the low risk class. That is because of the time it took for resistant populations to evolve, despite widespread use, as well as a feeling that a minimum of resistance management planning can preclude problems of resistance.

Prognoses for Particular Herbicide Groupings

Phenoxy herbicides - low risk. 2,4-D, MCPA, and MCPB have been used for many years. They are probably multisite inhibitors or if single site, then resistant individuals are probably highly unfit. These herbicides are often considered to be "auxin like" because of auxin type action at low concentrations and growth deformations at high concentrations. Quinclorac, due to similar symptomology is classified in this category (Worthing and Hance 1991), yet quinclorac does control grasses while 2,4-D, MCPA/B do not. Except for quinclorac, the phenoxyes have low persistence allowing late flushes of susceptible weeds to develop. They do not give perfect weed control, but in many situations give cost-effective control. If farmers try hard enough, they can and do get resistance, but a minimum of caution (often fortuitous) has precluded evolution of resistance elsewhere; e.g. crop rotation or use of another grouping about every 5 years. The phenoxy herbicides would make good mixing partners with any low risk herbicides with a similar weed control spectrum. They would also make good partners for high risk herbicides having the same biological persistence, including for the broadleaf weeds and sedges inadequately but partially controlled by phenoxy herbicides.

Thiocarbamates - low risk. Thiobencarb and molinate have been used for a very long time without major resistance problems. Presumably esprocarb, pyrobuticarb, and dimepiperate have the same multiple sites of action and short biological persistence, all properties that lower risk. Still, farmer persistence has made up for lack of biological persistence, and some grass weeds of small grains have evolved resistance to triallate (a thiocarbamate) in wheat and to molinate in rice, after decades of non-stop usage, in limited areas. Caution should not be thrown to the wind. Previously described results have shown that there is a complementarity between thiocarbamates and propanil in killing resistant *Echinochloa*. Presumably such mixed formulations will provide effective protection against evolution of resistance to both herbicides, for a very long time, if they are used.

Acetamides - low risk. Chloroacetamide herbicides are among the most widely used grass killers available, and have been used for many years. No cases of resistance have been reported following direct selection by these herbicides. Still, these herbicides are degraded in crops, and the degradation pathways can be stimulated to higher levels by chemicals (so called herbicide safeners, antidotes or protectants). Indeed, fenclozim is used to safen pretilachlor in rice. Pretilachlor and butachlor are used mainly against grasses but also control some broad-leaf weeds and sedges. There is good reason to expect that some weed will evolve elevated levels

of the enzymes that degrade the chloroacetamides used in rice. Indeed, two *Lolium rigidum* accessions selected for resistance mainly to trifluralin had an approximate 6 fold cross-resistance to alachlor, metolachlor and propachlor, as well as to herbicides of other groups (Burnet *et al.* 1994). Butachlor has the saving grace of having a relatively short biological persistence, which should delay the evolution of resistance to grass weeds having multiple flushes of germination throughout the season.

There is no information about whether phenylacetamides such as mefenacet or butylamides such as bromobutide have the same target(s).

Protoporphyrinogen oxidase (protox) inhibitors and other bleaching herbicides - low risk.

Diphenylether type, as well as various herbicides with diverse chemistries inhibit the chloroplast isoform of this enzyme. The rice herbicides inhibiting this enzyme are chlornitrofen, nitrofen, and oxadiazon. (Nitrofen has been removed from the market). Some pyrazole herbicides are known to inhibit this site (Sherman *et al.* 1991) but others do not (Schulz *et al.* 1993). The symptomology of bleaching of the pyrazoles used in rice suggests that benzfenap, pyrazoxyfen and pyrazolynate inhibit the enzyme *p*-hydroxyphenoxyphenylpyruvate dioxygenase and not protox. Weeds are not known to have evolved resistance to any of the protox inhibitors under selection pressure of these herbicides, although weeds that evolved to another photooxidant generating herbicide have a small amount of cross-resistance to herbicides of this group (Shaaltiel *et al.* 1988). Algal mutants with a dominant target site mutation conferring resistance to protox inhibitors have been isolated (Oshio *et al.* 1993). Thus, it may be a matter of time until such mutated populations appear in higher plants, unless the mutation is highly unfit. It should not be easy to evolve a metabolic resistance to any bleaching herbicides. Some herbicides kill slowly, and the plant has time to detoxify them and recover. The death from protox inhibitors and other bleaching herbicides is very rapid and these herbicides would have to be rapidly degraded so as not to damage the weed. Still, rice must have the capacity to do so, so weeds could mimic the rice. Oxadiazon in theory should be a good mixing partner for any at risk herbicide with a similar weed control spectrum, because of its long duration of biological persistence.

Photosystem II inhibitors - low and medium risk herbicides. Bentazon, propanil, dimethametryn, simetryn (and possibly daimuron) all have as their primary site of action the D-1 protein of photosystem II. Target site mutations at this site are exceedingly rare. It took a decade of repeated treatments of tens of millions of hectares of maize, roadsides, and groves with the most biologically persistent of these herbicides for resistance to evolve. Based on this, there is a very low risk of evolution of those PSII inhibitors that are short lived, such as propanil. Still, there are other ways to evolve resistance to these herbicides, and that is what seems to have happened with propanil. There is no cross resistance to other PSII herbicides, and propanil resistant weeds initially show signs of inhibition before recovering, both suggesting that resistance is metabolic and not target site. The very long persistence of dimethametryn, and the fact that all species resistant to PSII herbicides were selected by *s*-triazine herbicides such as dimethatryn and simetryn, suggests that they should be classified as medium risk. Their low to medium risk render them good mixing partners, when other criteria are met.

Tubulin binding herbicide-pendimethalin - medium risk. The medium risk dinitroaniline herbicides are widely used for grass control. There are no reported cases where resistance has evolved to this group where they were used in rotation. Conversely, monoherbicide use lead to

target site resistance in two major grass weeds and to a seemingly metabolic resistance in another. The long persistence of pendimethalin means that it exerts season long control and thus a high selection pressure. The possibility of its use in wheat in wheat/rice double cropping is ominous, unless there will be herbicide rotation. The long persistence also indicates that it will be problematic to find mixing partners that will meet the criteria delineated above for weeds germinating in multiple flushes.

Acetolactate synthase (ALS) inhibitors - high risk for resistance. The rapidity with which many weeds in wheat, soy, rice and along roadsides over large areas have evolved resistance to this group of herbicides is ominous. Both target site and metabolic resistances have appeared. The long persistence of the major ALS inhibitor used in rice (bensulfuron-methyl) means that it will be hard to find a mixing partner of lesser risk, with a similar persistence. No potential mixing partner has the same weed spectrum. The simultaneous use of bensulfuron-methyl with dimethametryn for broadleaf weeds and pendimethalin, oxadiazon and/or thiobencarb (on paper) may give an adequate overlap of weed spectra and persistence. It is probably unadvisable to use any ALS inhibitor in more than one out of three years in rice monoculture from a resistance management point of view. This should be sufficient to set back those weeds not controlled by other herbicides, and keep these excellent herbicides around for a longer period. Whether such rotations will allow for a greater number of ALS-inhibitor treatments than monoherbicide culture, until resistance evolves, is an open question. Still, it will delay resistance until more shorter persistence ALS inhibitors come on market. In theory, these should exert less selection pressure and thus delay the duration of use until resistant weed populations evolve.

Acetyl CoA carboxylase (ACCase) inhibitors - a high risk group. Fenoxaprop-ethyl is the only ACCase inhibitor being marketed for rice at present. It is already widely used in wheat (with a safener) and has selected for resistance in the grass weeds that it heretofore excellently controlled. This is despite the short persistence of all ACCase inhibitors, which are mainly foliarly active. Thus, any grass weed that has a single flush treated with ACCase inhibitors is likely to evolve target site or seemingly metabolic resistance, as has happened elsewhere. There are several grass-killers that are not as risky that are potential mixing partners. One must be careful of inter-herbicide antagonisms. Many antagonisms have been reported between ACCase inhibitors and other wheat selective herbicides.

Hard to classify herbicides. Too little is published about many grass herbicides to classify them. We tentatively classify naproanilide as low risk, based on its low persistence. Quinclamine, a quinone, probably inhibits PSII in plants (based on its structural similarities to other quinone herbicides). It can probably also inhibit other plant pathways as it is also a fungicide, and fungi lack photosynthesis. Thus, it may be a low risk herbicide. The site of action of piperophos, an organophosphate herbicide, has not been reported. With its very long persistence it should exert strong selection pressure. Strong selection pressure is immaterial, if there are no genes for resistance in the weeds. Rice has the genetic capacity for resistance to piperophos and insects have rapidly evolved resistance to organophosphate insecticides. If this herbicide is overused, there may be resistance problems.

Prognoses for Resistance to Widely Used Herbicide Mixtures

A large number of the mixtures in use for rice contain herbicides that separately control broadleaf weeds, sedges and/or grasses. The herbicides in such mixtures have no overlapping weed spectra and thus each herbicide should be considered separately. Other mixtures should be analyzed against the predominant local weed spectra.

Weeds Most Likely to Evolve Resistance

The history of weed control is fraught with cases where minor weeds became major weeds after older, low risk herbicides controlled all their competitors. The newer, high risk herbicides controlled them, and selected for resistance. This seems to be what happened in California with bensulfuron-methyl. Prior to its use, *Sagittaria montevidensis* and *Cyperus difformis* became problem weeds, which bensulfuron-methyl excellently controlled. As stated before, the best recommendation that can presently be made is to use the at risk herbicide a single time, not more often than once in three years, when the problem weed gets out of hand. We discuss below other such weeds that may evolve resistance problems are they are controlled by only a few or by at-risk herbicides.

Grasses. *Echinochloa* spp. are probably the major problem species in rice and are a major target for herbicide development because of inadequate control. Thus, very large populations of seed must be present from which to select resistance whenever a new herbicide is introduced. *Echinochloa crus-galli* has already evolved resistance to triazine herbicides in four European countries, two states in the U.S.A. and in Israel (LeBaron and McFarland 1990). *E. colona* biotypes resistant to propanil have been found in Japan and Columbia (LeBaron and McFarland 1990) and more cases should be expected, considering the widespread usage of this herbicide.

Thus among grasses, *Echinochloa* spp. remain with the "highest risk", particularly with the possibility of more evolution of propanil resistance. One of the herbicides that excellently control the propanil-resistant biotype, fenoxaprop-ethyl, is a high-risk herbicide. Cases of resistance in *Echinochloa* spp. to two alternatives, quinclorac and molinate have been reported. If molinate (a thiocarbamate) remains the only grass herbicide used in California, resistance problems may likely appear. In the southern U.S. pendimethalin can be used besides thiobencarb, while Asia has several more low risk choices from two chemical groups (butachlor and pretilachlor, chlornitrofen and other diphenylethers), in addition to thiobencarb and pendimethalin.

The use of the high-risk herbicide fenoxaprop-ethyl may remain the only alternative to control other problem grasses, *Leptochloa* spp. and *Ischaemum rugosum*. The currently used herbicides that control *Echinochloa* spp. either provide only partial control of *Leptochloa* spp., (propanil, molinate, butachlor, pretilachlor) or totally fail to control it (quinclorac). Thus, in the course of a growing season, once *Echinochloa* spp. are controlled, *Leptochloa* spp. predominate. The build-up of *L. panicoides* and *L. fascicularis* was observed in the U.S. and of *Leptochloa chinensis* (Roth) Nees in certain parts of tropical Asia. Thiobencarb and fenoxaprop-ethyl are the two currently registered grass compounds left as alternatives for control of *Leptochloa* spp. Of these, fenoxaprop-ethyl controls it excellently but is a high risk, resistance-prone compound. *Ischaemum rugosum* populations are increasing in Latin America and certain parts of tropical Asia. In Latin America, this weed germinates much later than rice and escapes preemergence treatments, leaving the post-emergence high-risk grass herbicide fenoxaprop-ethyl as probably the only alternative.

Broadleaf weeds. Populations of perennials are building-up, due to the continuous use of older herbicides (i.e. phenoxys) for the control of annual broadleaf weeds. Two difficult to control perennial broadleaf species are increasing in populations in temperate Asia; *Sagittaria trifolia* and *S. pygmaea*. Of the herbicides used for broadleaf control (2,4-D, MCPA, bentazon, bensulfuron-methyl, pyrazosulfuron), the resistance prone sulfonylureas are probably the best alternatives in terms of efficacy. This is probably the case in Taiwan, where phenoxys are seldom used leaving bentazon and sulfonylureas as alternatives. Because *Sagittaria montevidensis* has been quick to evolve sulfonylurea resistance in California, there is also a great probability that *Sagittaria* species (*S. trifolia* and *S. pygmaea*) will evolve resistance elsewhere to the sulfonylureas.

Difficult to control perennial sedges, *Eleocharis kuroguwai*, *Scirpus juncooides*, and *Cyperus serotinus* are also increasing in populations. Since *C. serotinus* belongs to the same genus as *C. difformis*, a sedge that evolved resistance to bensulfuron-methyl in California, it may have a similar genetic make-up and *Cyperus* spp. are likely to evolve resistance to sulfonylureas elsewhere.

CONCLUDING REMARKS

After 30 years of use, the worlds' worst weeds of rice, *Echinochloa* spp. evolved resistance to propanil in the Americas and Europe. After 5 years or less of use, a broadleaf weed *Sagittaria montevidensis* and a sedge *Cyperus difformis* have evolved resistance to bensulfuron-methyl in a goodly proportion of the areas where the herbicide is used in North America and Australia. In Asia, no major resistance cases have yet been reported in its two heaviest user countries, Japan and Korea. There have only been sparse reports in China, Malaysia, and Philippines of evolution of resistance to herbicides such as 2,4-D and butachlor, which were used over wider areas and for longer periods. This may be due to the wider variety of herbicides used in Japan and Korea.

There is a trend towards faster evolution and more widespread cases of resistance in the Americas and Europe where less than 10% of the rice is grown, and only isolated cases in Asia where 90% of the rice is grown even in intensive herbicide using countries such as Japan and Korea. A comparison of the herbicide use patterns and crop cultural practices would help explain this occurrence.

Probably the most important differentiating factors are:

- 1) fewer choices of herbicides and herbicide mixtures in America, than in Asia;
- 2) greater use of the new, high-risk herbicides in America than in Asia;
- 3) large farm areas and high cost of labor make herbicides the best economic alternative in America; and
- 4) the only, or major, rice culture method in America is direct-seeding, (vs. transplanting in Asia) where rice and weeds emerge and grow at the same time, favouring intense weed competition. This is especially acute in dry-seeded rice where there is no paddy water for the first 4 weeks. With direct seeding there is a greater need for chemical weed control, with the most potent and most persistent compounds.

The increasing trend towards direct-seeding in Asia may shift herbicide use patterns and contribute to faster evolution of resistance. Current estimates show that 80 to 100% of direct-seeded rice areas in Sri Lanka, Thailand, and Malaysia are treated with herbicides and this is expected to increase as well in other Asian countries. *Fimbristylis miliacea* evolved resistance

to 2,4-D in direct-seeded rice fields in Malaysia. The increase in dry-seeding in Korea will probably result in increased use of propanil, a low-risk compound, unless used too often. A wider choice of herbicides for direct-seeded rice would be needed to manage expected resistance problems, in addition to cultural practices. Crop rotation would greatly delay resistance, but it is not popular in some irrigated areas where two rice crops per year are grown. Such intensity engenders resistance. Thus, resistance has come to Asia, and may likely be a greater problem as both the agronomy and herbicide use patterns change.

The sulfonylurea herbicides have been a godsend for the control of sedges, which were poorly controlled by earlier herbicides. The residual effect of the sulfonylureas allowed nearly full season sedge control, and greatly widening the window of control. This will be their shortcoming, because of the high mutation frequency for resistance, the high selection pressure, and the large populations that have built up will allow for rapid evolution of many more resistant populations, wherever these herbicides are used. ALS inhibitors with less persistence mixed with less vulnerable herbicides that effect some control might considerably delay resistance.

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CHAPTER 14

THE ECOLOGY OF RICE WEEDS - AN OVERVIEW

THE ECOLOGY OF RICE WEEDS - AN OVERVIEW

A.M. Mortimer

INTRODUCTION

Rice (*Oryza sativa*) is one of the most important and versatile staple food crops of mankind. Yet as a production system, rice cropping remains consistently at risk. Of the pests that threaten rice yields, weeds are the sole example which almost always exceed an acceptable level in every season (Moody and Cordova, 1985).

It has been argued in the literature that of the circa 30 thousand species of plants considered as weeds world-wide, 50 - 200 may appreciably damage the majority of food crops but it is only 10 species which cause the majority (at least 80%) of crop losses. Whilst three of these ten (*Cyperus rotundus*, *Echinochloa crus-galli* spp., *Imperata cylindrica*) can be found in poorly managed rice fields, it is misplaced to assume that a narrow subset of weed species is common to all major rice cropping systems. As with the weed flora of other arable cropping systems, a diversity of genera are present, but particularly so in the case of rice because of the extraordinarily wide range of climatic and cropping conditions in which the crop is grown. Over 1,800 species have been reported as weeds of rice in south and south-east Asia (Moody, 1989) and by way of example Table 1 illustrates the principal species in weed communities of rice in relation to cropping system in the Tamil Nadu in India. Whilst emphasising those species that tend to be ubiquitous in rice crops and may be considered as 'major' weeds, it also highlights the distinction that upland rice weed communities comprise more graminaceous weeds than communities of other systems. Seasonal variation in water availability and temperature at least also play a major role in defining habitat conditions which determine weed floras. Table 2 provides a comparison of the relative abundance of a range of important weeds in wet-seeded (pre-germinated) rice culture in Assam, India. Several authors (e.g. Moody and Drost, 1983) have noted the greater abundance of dicotyledonous weeds associated with transplanted rice and their lesser abundance in wet seeded rice.

At first and second sight then, rice weed communities appear as complex ecological entities which are a natural hazard to mankind (Mortimer, 1990). The diversity of rice growing systems and associated breadth of weed communities of rice prohibits an exhaustive analysis in a short review and this paper focuses on selected processes in the ecology of rice weeds to illustrate the role of ecological studies in understanding the dynamics of populations and communities.

The construction of a weed flora - ecological and evolutionary perspectives

Interspecific selection on ecological time scales

Ecologically speaking, the construction of a weed flora is an artifice of man. Particular weed species occur in cropped land as a result of agriculture acting as a force of interspecific selection. Land cultivation is often a key component in the selective process as it promotes the emergence of non-crop species close to the time of crop planting. Both past nomadic and present-day shifting agriculture illustrate that the initial weed flora of previously agricultural virgin land reflects those indigenous species that are naturally present in the soil as dormant propagules. Subsequent cropping of the same land imposes on this initial flora a complex of selective forces which derive from the crop husbandry practices used to maximise crop yield. Whilst it is hardly surprising that different rice weed floras arise because of different agricultural practices in different locations in the

world, understanding the mechanisms by which such communities are both built but also change involves ecological questions concerned with species pre-adaptation and species migration. Pre-adapted species (*sensu* Mortimer, 1990) are those which are naturally resident in an agro-ecosystem within dispersal distance of cropped land and become incorporated into a weed-crop community as a consequence of the use of a suite of crop husbandry practices. On the other hand, weed floras may result from invasion of alien species, analysis of which involves examination of dispersal vectors. For example, of the introduced rice weed species in the USA all that have entered into the state of California, with the exception of *Echinochloa crus-galli* have arrived in contaminated rice seed (Fuller and Barbe, 1983).

Selection on evolutionary timescales

The evolution by natural selection of weeds may be seen at three levels (Mortimer, 1990): by direct speciation of weeds possibly preceded by hybridisation events between weeds and crops; by differentiation at population and genotype level within weed populations; and through crop mimicry as a result of coevolution under the hand of man.

Weedy rice forms are widespread in many counties and interfere with rice production due to competitiveness in reducing yields. They are particularly difficult to control because of a number of undesirable characteristics such as seed dormancy and early seed shattering from the head. Whilst in many cases the precise evolutionary history of weedy rices remains obscure, they illustrate in part the first two evolutionary processes. In temperate regions (China and Korea) weedy rices are thought to have evolved from rice (*Oryza sativa* L.) and Abdullah *et al.*, 1991 have shown, using molecular markers, that a recently discovered weedy rice population in Malaysia had very similar genetic structure to the cultivated rice. In such situations, the extent to which there is regular gene exchange in both directions is unknown but it is often noted that there is extensive intrapopulation variation in morphology.

In areas where rice and wild rice populations are sympatric the origins of weedy rice is more problematic. In Asia, rice is thought to be derived from common wild rice (*Oryza rufipogon* Griff, the Asian form of *O. perennis* Moench) and progenies of hybridisation between this species and cultivated rice are weeds of lowland rice (Morishima, 1987). Common wild rice exhibits wide variation in life-history traits and may exhibit annual, intermediate and perennial ecotypes (Barbier, 1989) and resultant hybrids with rice cultivars are thought to be an important progenitor of weedy rice in Thailand and India (Oka and Chang, 1961, Watanbe 1995).

In evolution by crop mimicry the weed functionally imitates the crop so that the selective agent (man) is deceived. Yabuno (1983) considers that hand weeding may have played a major role in the artificial selection of rice mimics by *Echinochloa* species in Japanese rice nurseries.

Chapter XXX considers the evolution of herbicide resistance in rice weeds which affords an example of evolution through population differentiation.

Population ecology

It is only those species that can exhibit stasis or net positive population growth over successive cropping seasons that become persistent weeds. In monoculture cropping such as continuous rice, weed species display population structures that change noticeably over a cropping season. Typically dominated by reproductive propagules in crop fallows, the structure alters throughout the life of the crop with the emergence of weed seedlings or shoots, the survival of young plants and the

subsequent maturation of adult reproductive individuals. Both periodicity in cropping and cropping practices may result in flushes of weed emergence giving discrete generations of individuals; but sometimes overlapping generations of weeds will occur where weed life cycles are markedly shorter than the crop and the life history permits. This view applies to all weed species able to recruit new individuals from a cryptic reservoir of dormant propagules in the soil and both annual and perennial life forms may be represented in life tables that describe the flux of individuals from one stage of the life cycle to the next (Cousens and Mortimer, 1995).

Such life tables are convenient devices to classify the developmental stages in the growth of the plant as a prelude to calculating population growth rates (Begon *et al.* 1996). To calculate the change in population size (per capita growth rate) it is necessary to compare population sizes after a known period of time. Where possible, it is convenient to identify a point in the life cycle of the weed where the population is composed of (ideally) one type of structure (e.g. dormant seeds in and on the soil) and to calculate rates of increase from census estimates (per unit volume or area) taken for instance at the start of successive generations of growth. In the simple case of a monocarpic weed species reproducing exclusively from seed there are two contributions to rate of increase - the fraction persisting in the seed bank from previous generations and the contribution from seed reproduction by surviving plants from the current generation. Perennial stage-structured populations can be treated in the same way but are necessarily more complex.

Just why a particular cropping practice should realise a niche for one species and not another may in part be deduced by direct autecological comparison and by experimentally measuring fitness (survival and reproduction) in appropriate (competitive) environments over generations of population growth. Ecological analysis of the population dynamics of individual weed species involves an examination of the effects of management practices and companion species on the flux of individuals over the various phases in the life cycle. We are therefore interested in: a) propagule persistence in the soil, b) recruitment of new individuals by seedling establishment or shoot emergence c) survivorship to reproduction and d) fecundity seed or vegetative propagule production. with the ultimate aim of examining population growth rates.

There is however a considerable lack of information on the biology and ecology of many weeds occurring in rice in the tropics (Moody 1993). This is not to imply however that the speed of change in weed abundance is unappreciated. Velasco *et al.* (1961) reported that in the Philippines whereas most of the weeds found in upland rice in the first crop following bush fallow clearance were dicotyledonous, during the second cropping season monocotyledons predominated. This phenomenon has been widely observed in upland rice elsewhere. Detailed observation has also shown that although the weed flora may be similar across a range of ecological zones, it is the relative abundance of the dominant grasses that varies according to environment. In a comparison of weeds in upland rice in West Africa, Akobundu and Fagarde (1978) found *Rotboellia cochinchinensis* was the major weed in one location whereas *Echinochloa colona* predominated in another. It is equally clear from the literature that whilst the consequences of a past change in crop management practices on weed floras are often known by farmer and researcher alike, the underlying dynamics and their causes are not.

Temporal processes

Propagule persistence in the soil

Dormancy in propagules buried within the soil confers longevity which in turn affords the possibility of recruitment of new plants into future weed-crop communities. Whilst the abundance of weeds present in the buried propagule bank at any one time will be the net result of gains from propagules dispersed into the soil and losses through *in situ* death and germination, it is the flux of individuals amongst the different dormancy states that determines the fraction of the buried population that may germinate at any one time. In rice weeds as in other agro-ecosystems species perennating from tubers or buds generally exhibit shorter longevity in the soil than those persisting as buried seeds (Table 3). Species propagating from seed display a wide span in longevity. The persistence of buried propagule populations may be quantified by measuring the 1/2 life (the time taken for a decline in the buried population by 50%) and is likely to vary with soil depth and rice management regime. Watanabe *et al.*, 1991 concluded that in the upper 10 cm of the soil in transplanted rice fields in Japan seeds of *Scirpus juncoides* declined by 30 % each year equivalent to a half life of 709 days whereas longevity was shorter in *Echinochloa oryzicola*, 365 - 157 days.

Both innate and induced dormancy (Harper, 1977) may contribute to longevity, induced dormancy being a predictive form of dormancy as a consequential response to changing environment (Begon *et al.*, 1996). A good example of this is seen in *S. juncoides* whose seeds are seasonally induced into dormancy during summer to autumn to be released during winter to spring. Soil conditions particularly aeration may strongly influence viability and hence longevity of seeds. Watanabe and Azmi Man (1995) noted that *Ischaemum rugosum* did not persist as viable buried seeds under continuously flooded or periodically flooded field conditions whilst 10.5% were still viable after 3 years (6 cropping seasons) in dry land.

For a species reproducing predominantly from tubers such as *Scirpus maritimus*, a widespread weed of lowland rice in Asia, Europe and temperate USA, deep ploughing provides effective weed control. This buries tubers at depths from which shoots fail to emerge, but in doing so enforces tuber dormancy which may last for at least two years.

In situ losses to the population due to failure to emerge from depth have not been extensively quantified. For some species we can infer however that they may be considerable. In field trials the emergence of *Echinochloa crus-galli* in transplanted rice was substantially reduced when the field was ploughed to a depth of 15 -18 cm compared to shallow rotary tillage (Arai and Matsunaka, 1968). The seeds of many of the more abundant rice weeds are relatively small (Noda *et al.*, 1994), the implication being that seed reserves limit emergence to the upper layers of the soil.

Plant establishment

The density of weed seeds in the soil of rice fields may be very high approaching 1×10^6 per m² where direct seeding of rice has been practised for several seasons (Ismael *et al.*, 1994). Such abundance far exceeds that usually observed in cropped land, including upland rice lands, which is may be two orders of magnitude lower (Watanabe, 1978). Equally the density of buried meristem populations encompassed by perennating organs (rhizomes, tubers and tap roots) may be large. Densities of 10,000,000 tubers per hectare have been estimated in *Cyperus rotundus*.

It would appear however that in general it is only a small fraction of the propagule reservoir that is recruited into the adult plant population each generation, 1-5% in *Echinochloa oryzicola*

(Miyahara, 1972) and 3 - 8% in *Scirpus juncoides* (Watanabe *et al.*, 1991). The available literature suggests that in some species it is seeds from the previous generation of weeds that contribute to most of the coming generation of weeds should conditions permit. Kim and Moody (1989a) reported that seeds of *Echinochloa colona* have no innate dormancy on dehiscence and will germinate almost immediately after harvest. In contrast in other species, seeds have innate dormancy and after-ripening periods are necessary for *Ludwigia octovalis* (20 days) *Echinochloa glabrescens* (50 days) and *E. crus-galli* spp. *hispidula* (> 60 days).

There is a substantive literature on the effects of water management and land preparation on the abundance of rice weed species (eg De Datta, 1981, Moody 1983). Both depth of land cultivation and depth of flooding can be used to minimise the fraction of the propagule reservoir that is recruited into the growing adult population.

Many weeds of rice will not germinate under water or saturated conditions but once established will grow in water, although appropriate depth of water can be ultimately limiting. Where there is year round water sufficiency and efficient water management, permanent flood and deliberately timed flood cultures in water seeded rice may be employed to maintain anaerobic conditions in the seedbed (Anon, 1987) and thus prohibit weed germination in some species. Smith and Fox (1973) observed that flooding to a depth of 5 cm was effective in controlling *Echinochloa crus-galli* in lowland rice cultivation and laboratory studies (MARDI, 1985) have shown that the germination capacity of freshly disseminated seed declines with water depth, 92% in 0 -1 cm; 68% in 2 cm ; 24% in 5 cm; and 4% in 15 cm, as does survival of pre-germinated seeds, but to a lesser extent (100% in 0- 2 cm; 65% in 10 cm and 32% in 15 cm). These data confirm the findings of Moody (1983) who concluded that the longer flooding is delayed after weed emergence in irrigated rice, the deeper the water must be to achieve even limited weed control.

The extent to which weed species of rice show substantive episodic emergence during the life of a rice crop which leads to flushes of new seedlings does not seem to have been recorded in detail. It is certain however that in direct seeded rice, cohorts of seedlings/shoots of weed species, particularly grasses (e.g. *Imperata cylindrica*) appear during the life of the rice crop, since more than one time of hand weeding is recommended (Moody and De Datta, 1982).

The mechanisms that result in cohort emergence may vary and be both biotic and abiotic. Fluctuating water levels during the early stages of crop growth in irrigated rice due to poor water management and/or lack of levelling, periodicity of rainfall in rain-fed rice and inversion of the soil profile leading to staggered emergence from propagules distributed at depth may all contribute. Somatic polymorphisms both in seed morphology and physiology have been recorded in *Echinochloa crus-galli* and *E. colona* (Roché and Muzik, 1964; Van Rooden *et al.* 1970) and are suggested by the ecotypic variation reported in other species. Flux amongst dormancy states plays a key role cycling fractions of seeds between induced and enforced states and thus the number of seeds available for germination. *Rotboellia cochinchinensis*, *Digitaria ciliaris* and *Eleusine indica* exhibit a peak of emergence early in the rainy season with subsequent small peaks linked with rainfall (Zimdahl *et al.*, 1988).

Growth and Reproduction

In the absence of deliberate post-emergence weed control practices and of weed specific herbivores, the chance of survivorship to reproductive maturity in weed species will depend upon competitive interactions amongst weed species and the rice cultivar. Noticeable density dependent

mortality in weed populations in annual arable grass weeds has only been observed at densities exceeding 20,000 plants m^{-2} and densities of this level might well be expected in direct seeded rice. Recognition of the over-riding importance of early weeding in the life of most rice crops to prevent yield loss implies that late emerging weeds are suppressed through crop competition but this may not necessarily lead to mortality in weed populations. Rather it may give stunted individuals that still survive to reproduce. Certainly the choice of density of planting (Roa *et al.*, 1977), fertiliser regime (Moody, 1981) and rice cultivar play a major role in determining size of weed plants. Smith (1981) showed that early maturing erect rice cultivars were more effective in suppressing weed growth than late flowering 'droopy' ones and Hoque *et al.* (1978) reported that *Fimbristylis miliacea* and *Cyperus* species were more dominant when grown in mixture with short statured plants as opposed to traditional tall cultivars.

The near total vegetation destruction of above ground biomass during and post harvest tends to select for weed species that mature before or at harvest. Flowering maybe extremely rapid as in *Cyperus iria* and *C. dehiscent* which may take as little as 28 days to flower from seedling establishment. *Echinochloa colona* may achieve production of mature seeds within 30-45 days under short day periods. Similarly weedy rices often display their presence in a rice cropping by flowering early.

Reproduction in weeds is often remarked upon as prodigious (e.g. Norris, 1992) and whilst this is undoubtedly so for *Echinochloa crus-galli* (Table 4) of equal but of more significance is the plasticity that rice weed species present. From comparative studies, *Monchoria vaginalis*, *Cyperus difformis*, *Fimbristylis miliacea* and *Echinochloa glabrescens* have been reported to begin flowering even when plants have achieved less than 10% of their maximum dry weight, seed production continuing for more than four months (Kim and Moody, 1989b). These studies also indicated that the allometric relationship between seeds production and plant size changed with fertiliser level.

Spatial processes

Whilst it is convenient to contemplate population processes within a given area devoid of migration events, in rice weeds movement of plants and propagules is potentially of major importance. Where populations or weeds are maintained by immigration, an understanding of the vectors governing dispersal is essential for weed control. In aquatic weeds such as *Eichornia crassipes* an alien migrant from Central Brazil into lowland rice growing regions in latitudes 40° N to 45° S, plant spread along irrigation canals arises through the drift of plants reproducing vegetatively by stolons (Harley, 1994). Seed production is also considerable in this species (Scunthorpe, 1971) Seeds being long-lived, innate dormancy being removed by a period of desiccation after which rapid germination occurs. The damage that arises from this weed is largely hydrological in its effect on irrigation systems. *Salvinia molesta* is another Brazilian migrant species into many tropical countries of Africa, Asia and the Pacific (Room, 1990). In common with *E. crassipes* spread is by water movement but this fern reproduces solely by rhizomatous growth on the water surface, doubling in size every seven days in tropical conditions (Room and Thomas, 1986). The damage that accrues from high infestations is both through reductions in light and nutrient availability for crop growth. Dramatically successful biological control of this weed throughout the world has been through the introduction of a natural enemy the weevil, *Cyrtobagous salviniae*, which has shown obligate host specificity often resulting its own local extinction after complete *Salvinia* destruction.

Irrigation water is often quoted as one of the major means of spread of weed seeds in rice ecosystems. Chadrensa (1988) argued that the absence of networks of irrigation canals in certain districts of Sri Lanka prohibited the spread and abundance of weeds. Frequently made, similar avowals are however at best anecdotal. Definitive quantitative evidence that dispersal of weed species through irrigation water is integral to the maintenance of meta-populations of weeds is absent, although clearly such dispersal is important in primary invasions and in re-invasions.

Migration of weed seeds through the use of contaminated crop seed is however well documented. The rapid spread of *Echinochloa crus-galli* and *E. colona* in Malaysia has been attributed to the use of contaminated rice seeds (Baki and Salleh, 1982) and Fajardo and Moody (1995) reported that the most common weed seed contaminants in rice in the Philippines were *Ischaemum rugosum* and *Echinochloa* species. In the Philippines whilst farmers rarely use their own seeds for more than three crops because of cultivar degeneration, neither do they routinely clean rice seed before planting. In consequence migration routes naturally persist by the exchange of seed between farmers and seed producers.

Weed community dynamics

Continuous rice production through the time-honoured use of drainage, irrigation and transplanting is a cultural measure that affords some measure of weed control in that non-aquatic weeds tend to be controlled by inundation and aquatic weeds by drainage. Some authors view puddling soil, transplanting of rice seedlings and flooding as basic operations designed for weed control under continuous cropping. Whilst it is true that these operations lead to a level of control (Mabbayad *et al.* 1983), continuous cropping is made possible by the nutrient flux cycling that arises from timed soil submergence. Where the periodicity in flooding and drained land is large two distinct weed communities may exist associated with the wet and dry seasons. This is particularly evident in the central plain of Thailand which is cropless for a large part of the year but may be under considerable depth of water during the paddy season. During the dry season, land is covered with annual grasses, species of *Sporobolus* being dominant. Flooding destroys these species and they are replaced in transplanted rice by mainly annual weeds particularly sedges. The above ground plant communities of the same land area may therefore oscillate in a potentially stable switching system between arrested secondary successional states. A parallel exists in upland rice where fallowing constitutes a break in cropping on the same land, the duration of the break determining the rate of decline of dominant weeds such as *Mikrancia micrantha* H.B.K. and *Chromolaena odorata* (Swamy and Ramakrishnan, 1987; Roder *et al.*, 1995). In this latter situation it is anthropogenic factors that are dominant in causing and arresting vegetation shifts whereas seasonal climatic change is at least as important as anthropogenic ones in most rainfed rice ecosystems.

The last twenty years have seen intensification in rice production with for example the increasing use of herbicides (see Chapter XXX), technological invention and in Malaysia, at least, with the introduction of sophisticated water management systems for direct seeded rice (Ho, 1994). Relatively rapid shifts in the weed flora have been recorded in all instances. In the Philippines perennial weeds such as *Scirpus maritimus* and *Paspalum distichum* have increased where herbicides have been used for several years to control susceptible species such as *Monochoria vaginalis* and *Echinochloa* species (Moody and Drost, 1983; Kandasamy, 1995). In Korea, the introduction of machine transplanting of rice has increased both the density of rice weeds and a change in the composition of the weed flora (Kim *et al.*, 1984).

The recent changes from transplanting to direct seeding in rice in south-east Asia have resulted in dramatic alteration in the abundance and distribution of weeds (Table 5). Direct seeding techniques cause weed communities to change in composition with the less competitive dicotyledonous weeds and sedges being replaced by competitive grasses which had previously occurred at low abundance along the edges of direct seeded fields (Ho *et al.*, 1994)

Weed management practices and population ecology

The foregoing discussion leads to three observations regarding the role of population ecology in the development of the understanding of the effects of weed management practices. The first is that changes in abundance of rice weeds can be extremely rapid both at population and community level. Secondly, all aspects of the production process of rice (the types or rice culture, cultivar grown, tillage, method of crop establishment, planting density fertiliser application and water management) in addition to explicit weed control practices (see Chapters XXX) are likely to interact in governing the ultimate trajectory in change of abundance of individual species (see Moody 1993 and Ho *et al.*, 1995 for succinct reviews of individual effects). Indeed it is for this very reason that integrated weed management is stressed for the control of weedy rice in particular (Watanabe, 1995)

Neither of these observations are novel. A third is: namely that despite the extensive research on weed control in rice there appears to be no published comparative statements about actual rates of growth of individual weed populations and more importantly about the sensitivity of individual phases in the life cycle of a weed to changes in management as it effects overall growth rate. The same can also be said for many weeds of temperate agriculture (Cousens and Mortimer, 1995). More often than not the effects of particular weed management practices are inferred from weed management studies of particular stages in the production cycle. It is only by study of the population ecology of species encompassing the entire life cycle that robust statements concerning change in abundance can be drawn. Autecological comparisons may prove valuable in highlighting possible reasons why one species increases in abundance whilst another does not. However they will be no substitute for the meticulous experimentation that is needed to understand the mechanisms underlying patterns of species co-existence in rice-weed communities.

Concluding remark

A review statement made by in an international meeting in 1995 concluded that "weed communities in different rice ecosystems remain largely unexplored wildernesses for ecologists". Venturing into such a wilderness requires an awareness that whilst communities may be structured by technologically driven events in agriculture, the ultimate reason for exploration is the goal of predictive understanding of weed abundance. Without that, understanding the stability of rice yields will remain under threat.

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Table 1. Weed species considered of most importance in rice cropping in Tamil Nadu, India (from Venkataraman and Gopalan, 1995).

		Species
Transplanted lowland rice		
Monocotyledons	Grasses	<i>Echinochloa colona</i> <i>E. crus-galli</i>
	Sedges	<i>Cyperus difformis</i> <i>C. iria</i> <i>Fimbristylis miliacea</i> <i>Scirpus spp.</i>
Dicotyledons		<i>Ammania baccifera</i> <i>Brachiaria spp.</i> <i>Cynotis axillaris</i> <i>Eclipta alba</i> <i>Ludwigia parviflora</i> <i>Marsilea quadrifolia</i> <i>Monochoria vaginalis</i> <i>Rotala densiflora</i> <i>Sphaeranthus indicus</i>
Direct sown flooded rice		
Monocotyledons	Grasses	<i>Echinochloa colona</i> <i>E. crus-galli</i> <i>Eleusine indica</i> <i>Paspalum distichum</i>
	Sedges	<i>Cyperus iria</i> <i>C. difformis</i> <i>Fimbristylis miliacea</i>
Dicotyledons		<i>Ammania baccifera</i> <i>Eclipta alba</i> <i>Ludwigia parviflora</i> <i>Marsilea quadrifolia</i> <i>Rotala densiflora</i>

Direct sown upland rice

Monocotyledons	Grasses	<i>Chloris barbata</i>
		<i>Digitaria sanguinalis</i>
		<i>E. crus-galli</i>
		<i>Echinochloa colona</i>
		<i>Eragrostis spp.</i>
		<i>Panicum repens</i>
		<i>Paspalum dilatatum</i>
		<i>Cynodon dactylon</i>
		<i>Leptochloa chinensis</i>
	Sedges	<i>Cyperus rotundus</i>
		<i>C. iria</i>
		<i>Fimbristylis miliacea</i>
Dicotyledons		<i>Amaranthus viridis</i>
		<i>Corchorus spp.</i>
		<i>Eclipta alba</i>
		<i>Euphorbia hirta</i>
		<i>Portulaca spp.</i>
		<i>Trianthema</i>
		<i>portulacastrum</i>

Table 2. The relative abundance (arbitrary scale based on density and biomass) in wet seeded rice in Assam, India (from Barua and Gogoi, 1993).

Weed species	Summer rice	Autumn rice	Winter rice	Deepwater rice	Winter terrace rice
	Rainy season	Late rainy season	Infrequent rains	Shallow submerged land persisting in winter season	Irrigated from bunded water
<i>Cyperus difformis</i>			9		140
<i>C. iria</i>			19	16	44
<i>C. pilosus</i>		38			7
<i>Echinochloa crus-galli</i>			14		27
<i>Fimbristylis miliacea</i>	27		110	112	79
<i>Hygroryza aristata</i>			22	136	
<i>Ludwigia perennis</i>	47		2	13	
<i>Monochoria vaginalis</i>	64		64		
<i>Oryza rufipogon</i>			9	103	19
<i>Panicum walense</i>	19	68	95		
<i>Sacciolepis interrupta</i>		43	13		
<i>Scirpus juncooides</i>	7	36	17		58

Table 3. The longevity of propagules of selected weed species in transplanted rice fields in Japan. Longevity was measured from field observations of persistence and experimental trials. From Watanabe and Azmi Man (1995).

Longevity in the soil	Species	Life history and propagule type
≤ 24 months	<i>Alisma canaliculatum</i>	P ; bud
	<i>Cyperus serotinus</i>	P ; tuber
	<i>Oenanthe javanica</i>	P ; bud
	<i>Potamogeton distinctus</i>	P ; tuber
	<i>Sagittaria pygmaea</i>	P ; tuber
	<i>Sagittaria trifolia</i>	P ; tuber
24 - 48 months	<i>Echinochloa crus-galli</i>	A; seed
	<i>Echinochloa oryzicola</i>	A; seed
	<i>Eleocharis kuroguwai</i>	P; tuber
> 48 months	<i>Alisma canaliculatum</i>	P; seed
	<i>Cyperus difformis</i>	A; seed
	<i>Cyperus serotinus</i>	P; seed
	<i>Lindernia procumbens</i>	A; seed
	<i>Monochoria vaginalis</i>	A; seed
	<i>Rotala indica</i>	A; seed
	<i>Sagittaria trifolia</i>	P; seed
	<i>Scirpus juncoides</i>	P; seed

Table 4. Upper limits to seed production by isolated plants of some selected species (data collated from a variety of sources).

Species	Seed production per plant
<i>Echinochloa colona</i>	6000
<i>Echinochloa crus-galli</i> ssp. <i>hispidula</i>	> 10,000
<i>Echinochloa oryzicola</i>	2000
<i>Eleusine indica</i>	4000
<i>Fimbristylis miliacea</i>	7000
<i>Rottboellia cochinchinensis</i>	2000
<i>Scirpus juncoides</i>	1500

Table 5 Changes in the weed flora and dominance from transplanting to direct seeding in the Muda area (Malaysia) over ten years (1979 - 1989). After Ho and Itoh, 1991.

	Season					
	1979	1982	1984	1984	1987	1989
Number of species	21	34	42	45	50	57
Number of genera	18	18	30	30	38	44
Number of families	13	14	19	17	22	28
Direct seeded area %	0.2	20.7	53.0	24.0	98.9	81.7
Dominant weed species *	M v	M v	F m	E cr	E cr	E cr
	L hy	L hy	M v	S g	E co	L c
	F m	F m	E cr	L hy	L c	F m
	C d	L he	S g	P a	S g	M c
	L f	S g	M c	L c	F m	M v

* C d - *Cyperus difformis*; E co - *Echinochloa colona*; E cr - *Echinochloa crus-galli*; F m - *Fimbristylis miliacea*; L c - *Leptochloa chinensis*; L f - *Limnocharis flava*; L he - *Leersia hexandra*; L hy - *Ludwigia hyssopifolia*; M c - *Marsilea crenata*; M v - *Monochloria vaginalis*; P a - *Panicum alexandrinum*; S g - *Scirpus grossus*.

CHAPTER 15

THE NEED FOR INTEGRATED WEED MANAGEMENT IN RICE PRODUCTION

THE NEED FOR INTEGRATED WEED MANAGEMENT IN RICE PRODUCTION

R Labrada

INTRODUCTION

In the introduction to this book the importance of rice as a priority crop in many developing countries, particularly in Asia, was highlighted.

The growth of the world's population is expected to exceed 8.5 billion by the year 2020 and subsequently, this will require increased rice and other food production. This could be satisfied, either by increasing areas of the crops or by achieving higher crop yields. The first option may not be feasible for various economic and environmental reasons.

Flooded rice fields, which account for 95% of total rice production, release an estimated 25% of the methane (around 500 million tons) that reaches the atmosphere. Although the atmospheric concentration of methane is only 1.7 ppm, its molecule is able to trap heat about 30 times more effectively than a carbon dioxide molecule (IRRI 1991). Thus environmental concern about global warming will militate against increasing flooded areas. An increase in irrigated rice areas would require high capital investments, particularly for installing irrigation systems, and this does not seem feasible from an economic point of view.

Therefore increased production per cultivated area seems to be the only way to respond to this challenge, and this will require technological inputs to achieve needed production, but sustainable agriculture demands that these inputs should not affect the environment and resource base.

The population growth and increase of production cannot be, as well stated in the UNCED's Conference in Rio (1992), "combined with unsustainable patterns which place increasing stress on the life-supporting capacities". Hence technological improvements for increased crop production should be sustainable.

Such improvements should include land preparation methods aiming at soil fertility preservation, rational crop rotation and intercropping, introduction of highly productive cultivars with a degree of resistance to common pests and integrated pest management with rational use of pesticides including, probably, the use of new biological or non-conventional control methods.

Within the context of IPM special emphasis should be given to weed control in rice. In the previous chapters of this book it has been shown that weeds are one of the limiting factors in rice production and the need for integrated weed management has been endorsed by several authors.

Weed management practices should be technically sound, also economically feasible and environmentally friendly. Integrated weed management is the only sustainable way to increase rice production without affecting the surrounding environment.

MAJOR WEED SPECIES IN RICE

In rice fields the prevailing weed flora depends on various factors: climatic conditions, type of soil and cropping system. There are certain weed species with similar crop requirements to rice, some of them occur in any crop rice modality and there are others only prevalent in certain conditions.

Geographically, weed species such as *Echinochloa crus-galli*, *E. colona*, *Eleusine indica*, *Ischaemum rugosum*, *Paspalum distichum*, *Eclipta prostrata*, *Cyperus iria*, *C. difformis*, *Scirpus* spp. and *Ludwigia* spp. occur nearly everywhere in rice fields.

Monochoria vaginalis, *Leptochloa chinensis*, *Echinochloa glabrescens*, *Sphenoclea zeylanica*, *Dinebra retroflexa*, *Ammannia* spp. and red rice are major weeds in the Near East and Asia.

In West Africa, *Pennisetum subangustum*, *Paspalum scrobiculatum*, *P. vaginatum*, *Imperata cylindrica*, *Leersia hexandra* and *Rottboellia cochinchinensis* are also prevalent in different rice ecologies.

Species such as *Rottboellia cochinchinensis*, *Echinochloa colona*, *Eleusine indica*, *Imperata cylindrica*, *Cynodon dactylon*, *Paspalum scrobiculatum*, *Dactyloctenium aegyptium*, *Digitaria* spp., *Cyperus rotundus*, *Commelina benghalensis*, *Amaranthus* spp., *Euphorbia* spp. and others are mainly prevalent in upland conditions.

Frequent lowland rice species are *Echinochloa crus-galli*, *E. glabrescens*, *Paspalum distichum*, *Ischaemum rugosum*, *Leptochloa chinensis*, *Leersia hexandra*, *Cyperus difformis*, *C. iria*, *Scirpus maritimus*, *Fimbristylis miliacea*, *Eclipta prostrata*, *Monochoria vaginalis*, *Ludwigia* spp. and *Sphenoclea zeylanica*.

Some weed problems have been created by the introduction of new cropping technologies or herbicides. This is the case of the incidence of *L. fascicularis* which has become important in areas repeatedly treated with propanil herbicide in the American continent. This plant is resistant *per se* to this compound and the use of propanil year by year has led to increased density in rice fields. This interference has compelled farmers to replace the use of propanil or to apply propanil mixed with other herbicides.

In the above region where direct-seeded rice is the main crop modality, red rice is by now the most troublesome weed. This is also a serious weed in direct-seeded rice of Egypt (Hassan *et al.* 1991b). Density of the weed increases year to year, if control measures are not carried out, due to natural crossing with cultivated rice. The interference of this weed also tends to reduce the quality of harvested rice grains.

In the USA it has been found that in a long season interference a single red rice plant per m² reduced grain yields of Lemont and Newbonnet rice cultivars by 178 and 272 kg/ha, respectively (Kwon *et al.* 1991). These grain yield reductions were due to decrease in panicle number and length and in number of grains per panicle.

LOSSES CAUSED BY WEEDS AND WEED COMPETITION IN RICE

According to DeDatta (1981) weed growth in unweeded rice plots reduces yield by as much as 37% in transplanted, 45% in rain-fed lowland direct-seeded and 67% in upland rice.

In India, losses of rice grain yields due to unchecked weed competition were reported to be 43 to 83% (Pillai and Rao 1974).

In upland rice weed competition is a major problem. Weeds may cause yield losses up to 87% (Prusty *et al.* 1990).

Crop yield losses from weeds usually are proportional to the amount of water, light and nutrients used by weeds at the expense of the crop (Moody 1978).

Rice grain production is significantly affected by the level of crop stand and extent of weed competition. Many of weeds prevailing in rice have similar growth requirements to rice plants and competition begins at an early stage of crop growth.

Weeds compete intensively with rice for light, water and nutrients. As Ampong-Nyarko and DeDatta (1991) stated competition occurs when one of the limiting resources falls short of the combined requirements of rice crop and weeds. Rice yields are greatly reduced when shading occurred at early growth stages and via stress from water shortage at any stage of crop development.

Weed competition varies according to the weed infestation, the ability of the crop cultivar to compete with weeds and cultural practices. Application of N-fertiliser plays an important role in the degree of grain losses caused by weeds. Greater yield losses are reported to take place at low and high levels of applied nitrogen than an intermediate level when poor weed control is practised (Moody 1981). At present there are various highly productive rice cultivars characterised by short stature which are commonly less competitive with weeds than traditional cultivars. These less competitive cultivars require more crop care regarding weeding than traditional ones.

Weed competition is critical during the first 30-40 days in direct-seeded rice. Weed-free rice plants during the above critical period become increasingly competitive with newly emerged weed seedlings. It is for this reason that weed control measures should be carried out during this critical period.

In rice seedbeds, weed competition to rice seedlings will depend greatly on the seeding rate and quality of rice seed sown. Weed control in seedbeds is extremely important to enable farmers to obtain high quality seedlings for planting. In transplanted areas rice should be weeded at least during the first 2 to 6 weeks after planting (Moody 1994). In any case, environmental conditions, crop establishment and competitive ability of crop cultivar, weed species and level of infestation decide the level of competition and the time and duration of weeding operations. Timely weed control is basic to good crop production. Farmers should be aware of weed competition criteria to effectively and timely control the weeds and to save labour inputs.

With the introduction of herbicides it was thought that problems caused by weed interference would be easily solved. Life has shown that still now there are many weed problems; some of them uncontrolled with the common herbicides selective to rice.

It is clear that an integrated approach for weed control is required. This approach should be fully compatible with crop management practices. Entomologists have promoted partial Integrated Pest Management (IPM) programs in various crops. Unfortunately, nearly all these programs lack either disease, rodent or weed control activities. Weed science has developed enough to implement Integrated Weed Management (IWM). It is already recognised that IWM is a part of the IPM and

also of the integrated crop management. Rice is a crop where the interactions between weeds and other pests decide the density of various pest organisms. Therefore IWM should not be neglected in any IPM program for this crop.

INTEGRATED WEED MANAGEMENT

Integrated Weed Management (IWM), as an essential part of IPM, is not an easy task for weed scientists. Rice is grown in different ecosystems: upland and lowland, direct-seeded on puddled or dry soil and transplanted. For each crop establishment method a particular IWM will be required. IWM should also be based on the prevailing weed composition and infestation.

Essential requirements for improved integrated weed management are:

Technically effective - containment of weed infestation to such a level which does not cause significant crop losses.

- Fully compatible with crop growth and with other IPM practices.
- Preventing the dominance of particular weed species resistant to currently implemented control methods.

Economically feasible - affordable for farmers with small inputs.

This economic requisite should also lead to social improvements, such as:

- Reduction of labour for weeding, in particular women and children's labour.

The last, and perhaps, the most important requirement in the long term is that the weed control practices should be,

Environmentally friendly - they should maintain environmental quality and subsequently:

- Preserving soil quality i.e. avoiding any adverse effect on the soil (erosion, salinity and/or harmful chemical residues).
- Not causing air pollution.
- Not causing any harm to wildlife.
- Completely safe to humans.

Components of integrated weed management

Preventive control methods.

- Weed control during the growth cycle of the crop based on breaking the weed's reproductive capacity, thus reducing the continuous build up of weed seeds in the soil.

Preventive measures are important to avoid the introduction of alien weeds into particular crop area. These measures are emphasised in nearly all weed science textbooks, but they are the least practised methods everywhere. Machinery, implements, manure, soil, animals and man are all factors in spreading weeds. To decrease new weed infestations it is important to prevent their

movement from one area to other. It is also useful to prevent fruit set of weeds growing in the foregoing crop.

Weed seeds and seedlings are commonly disseminated with transplanted rice seedlings. This was clearly observed by Rao and Moody (1988) in farmers' fields in Guimba, Philippines. The authors reported that the percentage of weed seedlings and shoots of *Echinochloa glabrescens* in bundles of rice seedlings to be transplanted ranged from 4.5 to 14.2% in the wet season and from 3 to 8.7% in the dry season. Subsequently, the use of weed-free rice seeds, land preparation and weed control of seedling nurseries were recommended.

For a farmer, it may be tedious to clean implements after an operation in another field; to wait some time for decontaminating the manure, or even to clean his clothes bearing weed seeds. Some practical education regarding weed reproduction and spread is important for farmers, emphasising that prevention would save labour time for weeding, in the long-term.

Weed control before or during the crop cycle consists of various methods aiming to increase the competitive ability of the crop, such as:

(i) **Cultural:** Crop rotation, inter-cropping, land preparation, seeding or planting competitive cultivars, seeding rate, plant spacing, fertiliser application, water management.

a) *Crop rotation.* Rice rotation with a dryland crop normally reduces the infestation of weed species adapted to grow in moist and wet conditions. In many parts of the world rice is already successfully rotated with legume crops. Rice rotation with soybeans or beans has been found effective in reducing the red rice infestation in many Latin American countries.

From the author's personal experience, in Pinar del Rio province in Cuba, beans are normally sown during the dry period after rice. Beans are treated with the herbicide trifluralin, mechanically soil-incorporated, which is highly effective against grass weeds, including red rice. This method provides good suppression of red rice infestations for the subsequent rice crop during the rainy period.

A cropping system of soybean and rice grown in alternate years for four years combined with effective herbicide treatments was proposed by Smith (1989) to control red rice infestations in the USA. Crop rotation of rice with legumes also increases nitrogen in soil. According to Pingali and Rosegrant (1994), mung bean and soybean are the most popular legumes used in rotation with rice.

In general, crop rotation helps to avoid the adaptation and dominance of troublesome weeds in rice.

b) *Land preparation.* There is no standard method for land preparation in rice. It differs according to the water availability and its management. In this context some procedures have been found useful.

Normally land preparation in wetland tillage systems consists of ploughing, harrowing, soil puddling and levelling. Puddling is an important operation to control several grass weeds and to enable fast establishment and tillering of transplanted rice. Moody (1983) reported that the most

important effects on weed growth in rice come from puddling and good water management, but today it is known that seasonal puddling leads to formation of hardpans in paddy soil. This will be discussed later.

In dry seeded rice, tillage is practised differently. It is mainly based on breaking soil clods encouraging weed early emergence. In India, in dry seeded rice, the stale seedbed method which prevents successive weed flushes before rice seeding is effective (Mukhopadhyay 1987; Moorthy 1992). This method consists of ploughing and producing a fine tilth by breaking clods with a plank. The latter brings about a uniform germination of weeds which were controlled a week later by shallow cultivation. Subsequently crop seeding is carried out.

Another important procedure is levelling. Moody (1994) indicated that when the field is not levelled rice seedlings cannot establish quickly in the low spots and weed will grow abundantly in the high spots. Correct levelling facilitates good fertiliser application and permits better distribution of water on the entire surface without submergence of the rice plants.

c) *Competitive cultivars.* Rice cultivars that emerge rapidly and grow vigorously, developing canopy, would be expected to compete better against weeds than cultivars lacking these attributes (Moody and Mukhopadhyay 1982).

In Egypt, in transplanted rice, seedling age at transplanting is another important characteristic to create more competition from rice. Hassan *et al.* (1991) recommended planting of 30-day old seedlings which resulted in increased tiller production per plant and, subsequently, improved competitive ability.

At present, besides physical competitive ability, research is also trying to develop rice cultivars allelopathic to weeds. These rice plants should be able to suppress some weed species through either their root exudates or leaf leachates.

Regarding the incidence of *Striga* parasitic weeds in rain-fed rice in Africa, research at Long Ashton Research Station (Bristol University, UK) is proceeding to develop resistant cultivars to these phytoparasites.

d) *Seeding rates.* High seeding rates enable early competition from rice plants against weeds. This seems to be effective so long as crop yields are not reduced, but the cost of seed must be taken into account.

Hassan and Rao (1993) reported that little influence on weed suppression was achieved by increasing rice seeding rate from 72 to 96 kg/ha, while a rate of 120 kg/ha, in general, increased weed control. The authors considered that this rate is convenient to control broadleaved weeds and *Cyperus difformis*.

In India, good results in weed control have been achieved with lower rice seeding rates. Moorthy and Mitra (1990; 1991) reported that 69 kg of rice seeds/ha proved to be ideal for optimal crop growth and yields. These authors again emphasised the importance of crop establishment in direct-seeded upland rice to achieve good weed control.

Seeding rate is also important in seedbeds. Usually rice seedlings suffer less from weed competition whenever high rice seeding rates are used.

e) *Plant spacing.* This will depend on cultivar and seasonal conditions to guarantee optimum crop development. In India, it has been found that spacing of 15 cm was superior to 30-45 cm, thus increasing rice competitive ability and tiller production in upland rice (Bhan 1968, cited by Mukhopadhyay 1987).

In the Philippines, 20 x 20 cm spacing is the most appropriate for manual transplanting (Ampong-Nyarko and DeDatta 1991).

In Egypt, the cultivar Giza-175 transplanted in narrow rows (10 x 20 cm) effectively suppressed weed competition (Hassan and Rao 1993).

In any case, a good rice stand is a requirement for good crop competition against weeds. Bare areas will be undoubtedly occupied by weeds.

f) *Application of fertilisers.* N-fertilisers are required for optimal growth of rice plants and they can be of use to prevent *Striga* spp. establishment.

Moorthy and Mitra (1990) found that weed problems are aggravated when all of the N is applied at seeding time. They recommended split applications of N-fertilisers: at seeding, active tillering, and panicle initiation to achieve maximum effectiveness in weed suppression. Sharma and Das (1993) recommended N-application (up to 40 kg of N/ha) when weeds are controlled during the first 40 days either with manual weeding or combined with an application of thiobencarb.

Application of fertilisers is a waste when weed control is not practised.

g) *Inter-cropping.* This may be with mixed or alley cropping.

Mixed cropping is sowing a mixture of crop seeds. It is recommended mainly for rain-fed upland rice. According to Pande *et al.* (1994) crops planted with rice include: pigeon pea, millet, yam, cocoyam, maize, sorghum, cassava, cowpea, groundnut and okra.

In India, Angadi *et al.* (1993) have achieved good experimental results using mixed crops of sunhemp (*Crotalaria juncea*), cowpea (*Vigna sinensis*), soybean (*Glycine max*) and *Sesbania* spp. with rain-fed rice direct-seeded. Crop seeds were mixed with rice seeds and sown in furrows 20 cm apart combined with one hand-weeding (30 days after rice emergence) or inter-cultivation (15 days after rice emergence) plus hand-weeding (as indicated previously). In all cases dry weights of weeds were significantly reduced and grain yields were equal to those obtained by farmers using herbicides plus one hand-weeding or hand-weeding twice during the first month of the crop cycle.

Alley cropping consists of rice seeding between rows of legume hedges. The latter when ready are pruned to 60 cm high and cuttings are incorporated in the soil. The main alley crops used in Africa and Indonesia are *Leucaena* spp., *Sesbania grandiflora*, *Calliandra calothyrsus* and *Flamingia congesta* (Pande *et al.* 1994). This practice maintains soil fertility and minimises weed competition.

h) **Water management.** This is important during the early stages of rice growth to control weeds.

Flooding up to 10-15 cm prevents germination of several weed species, but if flooding is maintained, some hydrophyte species may become a problem. Normally with deep flooding, grass weeds are eliminated, while some broadleaf species might become a problem. For this reason flooding and drainage are required to minimise the incidence of hydrophyte or hygrophyte weed species.

Echinochloa crus-galli, at the 1- to 3-leaf stages, is effectively controlled with a deep flooding (more than 10 cm) in broadcast direct-seeded rice in Egypt (Hassan and Rao 1993).

In transplanted areas with a good water management weeds are a minor problem.

(ii) **Physical:** Mechanical and manual removal.

Physical removal is a useful weed control method particularly for farmers with a small crop area and few resources.

Many farmers complement their weed control program with one hand-weeding. Manual methods are tedious, costly and labour-consuming. If practised in extensive areas, not less than 120 man-hours for a single weeding in one ha will be required. The same is true for rice seedbeds. Rice plants could be affected by hand weeding at early stages since many grass weeds are indistinguishable from rice seedlings (Fajardo *et al.* 1990); beside this, physical removal is impractical during the rainy season.

There are prototypes of rotocultivators for use in rice, but some of them are difficult to push and must be moved back and forth for proper operation. Recently IRRI has developed some mechanical weeders, such as Push Type Single- or Two Row Cono-Weeders. These machines have conical shaped rotors which create a horizontal back and forth soil movement in the top 3 cm of soil uprooting weeds and burying them. A single worker can weed twice as much with a Single Row Cono Weeder than with conventional rotary weeders, while with the Two Row Type productivity is three of four times greater.

(iii) **Chemical:** Herbicide application.

Chemical control is the youngest weed control method. Its development started 50 years ago with the post-emergence application of 2,4-D. At present the use of pesticides, including herbicides, is a polemic issue. Agronomists and farmers already experienced in this method claim its usefulness, while the environmentalists consider it a risk to the environment. However, there is no doubt that direct-seeded areas have been increased and the use of herbicides has become essential, particularly in rain-fed upland areas.

Rational use of herbicides in small rice areas will undoubtedly save part of the labour time and inputs of small farmers.

In all cases care is needed whenever farmers use any pesticide. This can be achieved with good training programs.

(iv) **Biological:** use of natural enemies or microorganisms to control specific target weed species.

Biological weed control is poorly developed in rice.

In Australia, successful experimental results have been obtained with the use of a mycoherbicide based on an endemic fungus to control such weeds as *Alisma lanceolata* and *Damasonium minus*. Spray inoculation of weed seedlings 35 days after sowing resulted in 45% reduction in total plant biomass (Cother and Gilbert 1994).

Utilisation of fish in rice farming system appears to be a sustainable approach for rice cropping and also for weed control. In Indonesia, good experimental results have been achieved in irrigated lowland rice in rice-fish farming systems (Pane and Fagi 1992). In this case, fingerlings of the common carp and grass carp, at an average size of 25 g and density of 2000 ha⁻¹ were released into rice-cum-fish plots. Subsequently the dry weight of weeds was similar to those in hand-weeded plots or those treated with MCPA. Good weed suppression was achieved with the combination of common carp and grass carp, in particular for *Leptochloa chinensis*, *Fimbristylis miliacea*, *Cyperus iria*, *Scirpus maritimus* and *Luchwigia* spp. The density of these species declined 45 days after transplanting.

Biological control is likely to be developed more in rice, but will not entirely replace other control methods. In rice, a good contribution would be to develop effective biological control agent against the *Echinochloa* complex.

(v) **Requirements for the implementation of Integrated Weed Management**

Integrated weed management (IWM) does not imply the mere sum of the methods described above. The point is to implement those methods compatible with rice cropping to effectively reduce weed infestations at the time of severe competition. They are to be rationally integrated according to weed species present and their density, soil conditions and crop requirements.

a) *Research* is needed to understand the autecology and interaction of important weed species with rice.

Germination, emergence, growth and propagules production of weed species under different conditions and growth stages of rice are important factors, to predict weed behaviour and to design control methods.

Economic thresholds of dominant species should also be studied. Such a research is useless when the weed flora is composed of various species but is useful when 95% of the weed density is made up of one species with a density of < 1 plant m⁻². If the population is higher the required action will be to apply the control measures.

Herbicide trials should not only give an idea of the efficiency of any treatment but also indicate resistant weed species too. From personal experience of the author good counting of weed species

in various trials always gives a good indication of this. Overall visual assessment of weed densities is not always suitable to this end.

Nowadays, some weed scientists claim that the use of transgenic rice plants resistant to some wide-spectrum herbicides such as glyphosate will help to reduce the stand of troublesome weed species. This is true, but herbicide resistant species will probably become a problem in time.

In the opinion of the author, it is better to practise rotational systems i.e. crop rotation and from time to time replacement of the herbicide in use to avoid resistance problems. This can be accomplished only when it is possible to foresee problems.

Weed research should conduct studies attempting to foresee future problems in the field. Weed population changes do not occur in one season. It takes time for the reproduction of resistant weed species and their establishment in the field. The lack of regular monitoring is a major reason for the magnitude of this problem.

As Ho *et al.* (1992) indicated the weed rice ecological relationship is never static and the continuous adoption of any particular practice causes a shift in dominance and distribution of weeds in rice. Therefore regular weed monitoring is an important aid in formulating new approaches for weed management in rice.

In addition, research should be regularly communicated by extensionists. One of the major problems in weed management is to advise the use of a weed control treatment for a particular field without having any idea of the weed flora or its density. Areas representing at least 10% of available crop area should be monitored from time to time to allow rational control decisions.

b) *Extension* should also be aware of the ongoing research. Results from research are useful only when they are transferred to farmers.

Farmers are commonly reluctant to introduce new technologies. Normally they believe that new technology is economically unaffordable or difficult to implement. Therefore, they should be persuaded through a comprehensive training program which should comprise various steps for introduction and dissemination of the results.

Demonstration trials together with the organisation of farmers' field days are required to introduce new research results. Details of weed species controlled with new treatments, yield increases and economic feasibility should be given to farmers in an understandable way. Many farmers may be illiterate and extensionists should be able to transmit messages in the simplest way. Group participation is best.

Usually when the results are effective enough and the farmers accept it, they, by themselves, will help in disseminating the results to other farmers.

This practice is applicable for IPM and IWM, but also for the introduction of other agricultural technologies.

(vi) **Constraints to IWM implementation**

a) *Awareness of weeds*

Weed control is usually neglected by official authorities in many developing countries. In many cases the officials might think that any development towards IWM will lead to social problems of unemployment. To accept that hand-weeding is enough for weed control is wrong.

For this reason weed research and extension receive little attention and financial support in these countries. The absence of these regular activities becomes a problem for IWM implementation and its improvement.

Emphasis needs to be focused on bridging the information gap between research and extension, monitoring weed infestations, herbicide effects on weeds, applying decision tools and system analysis, as well as implementing extension campaigns on IWM (Ho *et al.* 1992). In many developing countries there is a lack of infrastructure to develop what is really required. IWM will only be developed if weed research/extension bodies are either created or strengthened.

b) *Land preparation*

Soil is the main substrate for crop protection. Methods currently practised, sometimes repeatedly year by year, may affect soil fertility.

Particular attention should be given to upland rice grown in tropical conditions where soil erosion and water loss are major problems. Inappropriate cropping practices together with minimal use of organic manure reduce soil fertility.

Minimum tillage has several economic and environmental advantages.

According to Pande *et al.* (1994) this method, already practised in other cereals may be used in upland rice. It consists of opening a slot through the sod of the previous crop residue to enable rice seeding. With minimum soil disturbance seedlings carried out and the cover of residues of the previous crop will prevent emergence of weeds to some extent. It is best combined with band application of pre-emergence of early post-emergence selective herbicide; careful testing of herbicides should be carried out locally before widespread use.

The method preserves organic matter, soil moisture, soil structure and increases water infiltration rate. It prevents soil losses due to water and wind erosion and it reduces the energy required for crop production.

The major problem with this method is that perennial weeds such as *Paspalum distichum* and *Echinochloa stagnyna* become dominant. This will compel farmers to increase tillage frequency to minimise weed incidence for certain periods before coming back to minimum tillage. In such a case ploughing should be used to drag vegetative weed propagules to the soil surface for further desiccation under the effect of wind and sunlight.

In lowland areas puddling leads to the formation of hard pans (Pingali and Rosegrant 1994), which make it difficult to grow other crops in rotation. On one hand the rice crop suffers due to the poor ability of roots to extract nutrients from the subsoil and toxicities may occur due to the perennial waterlogged condition. On the other hand, poor establishment of short duration wheat in rotation

may take place after puddled rice. The hard pan may be broken and soil structure improved through application of organic matter but the subsequent rice crop will be affected due to reduced water holding capacity.

c) *Problems regarding the herbicide use*

From a practical point of view there is another constraint regarding the replacement of rotation of herbicides in use.

In certain developing countries herbicide active ingredients are bought and then formulation is carried out in the country. In these cases, the replacement is easy when it implies the same type of formulation i.e. EC (emulsifiable concentrate) by another EC or WP (wetttable powder) by another WP. It is more difficult when it is the replacement of a granular form since the substrate might be changed and this might not be locally available. The situation is extremely difficult when the herbicides are synthesised and formulated *in situ*. This may lead to economic problems.

Herbicides in use in rice are mildly toxic compounds, many of them with a relative short persistence in soil, and readily degradable in water under the effect of abiotic factors. Nevertheless, in the USA, perhaps, the country applying more herbicides than any other in rice, environmental concerns especially water quality, and increasing regulatory measures have slowed the development and registration of herbicides for rice (Hill *et al.* 1994).

An improved ground application method for herbicides is still needed for countries where applications by aircraft are practised intensively. In aerial applications part of the sprayed herbicide goes to the atmosphere, only part of it comes down to the ground, meaning that some atmospheric contamination takes place, but also that the herbicide rate required to effectively control the weeds is less than that actually sprayed. New, effective, less volatile formulations are needed with new ground application systems.

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Rice is the leading staple food crop in the world: one-third of the world's population depends on rice for nearly two-thirds of its food. Increased rice production is at present a necessity in many developing countries, and it can only be achieved by augmenting the yield per unit area and adopting highly productive and environmentally viable cropping technologies. Weed incidence is one of the major constraints to increased rice production; therefore, the improvement of weed management is an equally urgent need. The major emphasis of this book is on an integrated approach to weed management. It provides a survey of the current status of weed management under various systems around the world. The volume comprises 14 chapters devoted to the technical and economic importance of weed management in rice, weed management in different rice ecologies and the status of weed management in crops in different regions of the world. The biology of major weeds in rice, herbicide resistance and weed ecology are also addressed. The book is aimed at research workers, extension officers and development agents responsible for assisting farmers with weed problems in rice.

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